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THE TONGAPORUTUAN SEDIMENTATION IN CENTRAL HAWKE'S BAY

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Summary

The Mesozoic and Tertiary strata of Hawke's Bay include many sequences of vertically graded, banded sediments, some of which are contemporaneous with sequences of massive sediments deposited in nearby localities. The distribution of the thickness of sediments in Central Hawke's Bay, indicates that a trough-like basin existed in the upper Miocene. Into this basin a thick sequence of banded sediments was deposited, while at the same time a thin sequence of unstratified beds was laid down in the area surrounding the basin. An investigation of the grain sizes in the basin revealed a decrease in grain size in a westerly direction. The sediments were brought in from the east, presumably across a bar which is thought to have separated the basin from the open ocean.

Kuenen and Migliorini's theory that graded sediments are deposited by turbidity currents cannot be applied satisfactorily. The banded sequences of the upper Miocene and their massive equivalents show that these beds must have developed by a different mechanism.

Both the above mentioned basin and the bar subsided irregularly and intermittently, the basin subsiding more than the bar. As a result, the relation between bar-depth and basin-depth varied continually. Consequently there were changes in the speed and strength of currents across the bar. Grain size and the amount of sediment carried into the basin by these currents changed rapidly, causing banded sediments with vertical grading. The deposition of sediment continued in this way until the incoming current lost its power to transport coarse material. With the gradually diminishing carrying capacity of the incoming currents, increasingly finer sediments were brought in until current flow ceased almost entirely and only muds were laid down. With subsequent downward movement coarse material was again carried in. The system reflects an immediate lithological response to tectonic movement.

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It is not suggested, however, that all occurrences of banded sediments can be explained in this manner, but from what has been observed in banded sequences elsewhere in New Zealand, both in the Tertiary rocks and the Mesozoic and Paleozoic greywackes, it is considered to be a possibility.

INTRODUCTION

During fieldwork in Central Hawke's Bay (Fig. 1), a satisfactory explanation was sought for the genesis of the alternating sandstones and siltstones which, with massive unstratified muddy siltstones are common in the Mesozoic and Tertiary strata of the district. The upper Miocene rocks were selected for particular study as outcrops are abundant and their relationship to older beds reasonably well known. Upper Miocene banded sediments (Fig. 2) cover a considerable area, but massive, unstratified, calcareous, muddy siltstones of the same age occupy an even larger area in Central Hawke's Bay (Fig. 3).

Microfaunal studies, by N. de B. Hornibrook (pers. comm.) show that the Foraminifera of both the banded and the massive deposits are typical of the Tongaporutuan Stage. The fauna is so plentiful and well preserved that it is possible to divide the stage into a basal, middle, and upper part.

The following samples have been investigated for micro-faunal study:

Locality as in Fig. 19	N.Z.G.S. Microfossil No.	Age
II	F.7993	Upper Tongaporutuan
VIII	F.8075 and F.8077	Upper Tongaporutuan
IX	F.8074	Upper Tongaporutuan
X	F.8080	Upper Tongaporutuan
XI	F.7069	Upper Tongaporutuan
IV	F.7075	Mid.-Up. Tongaporutuan
XII	F.7063	Mid.-Up. Tongaporutuan
III	F.8035	Middle Tongaporutuan
V	F.7195	Middle Tongaporutuan
VII	F.7484	Middle Tongaporutuan
VI	F.7149	Low-Mid. Tongaporutuan
I	F.8044 and F.8045	Lower Tongaporutuan

Tuffite layers* are present in the basal Tongaporutuan in both the massive and banded sequence. Thus, judged by both paleontological

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*A general term for composite clastic rocks, in which both volcanic and detrital materials are present in considerable amount. HOLMES, A., 1920: "The Nomenclature of Petrology." Thomas Murby, London.

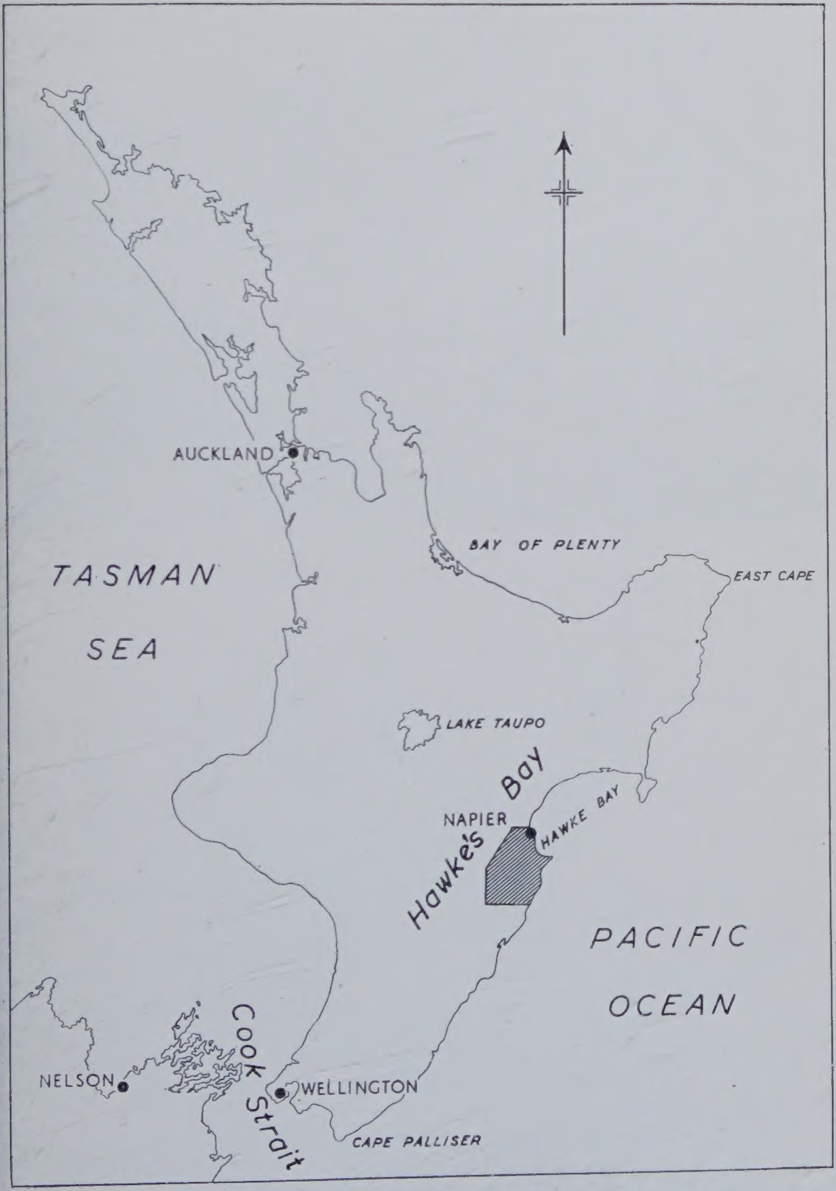

FIG. 1.—Map of North Island, New Zealand, showing location of Hawke's Bay area.

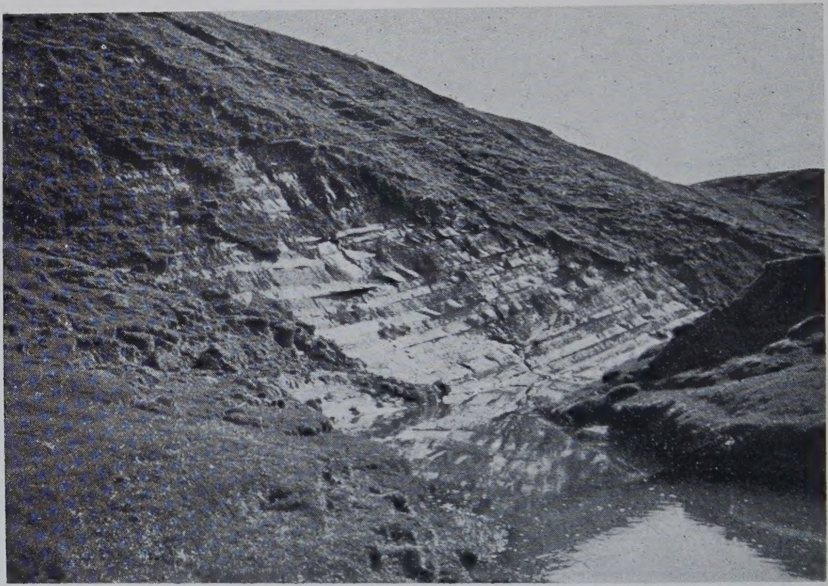

FIG. 2.—Typical outcrop of banded Tongaporutuan strata in Mangarara Stream, Central Hawke's Bay. Thickest bands in middle of outcrop are approximately 2 ft thick.

and lithological evidence, the two facies were laid down contemporaneously. The question therefore arises as to the reasons for the deposition of the two so completely different lithological facies.

The alternating Tongaporutuan beds, well exposed in the valleys of the Makara and Hawea streams and in the Silver Range, some 9 miles east of Otane Township (Fig. 3), will be here referred to as the Makara Facies. They reach a thickness of 10,000 ft, whereas Tongaporutuan beds of the massive facies in the Maraetotara District north-east of Elsthorpe Township are about 2,000 ft thick. The pre-Tongaporutuan strata were deposited in a shallow, broad geosyncline, in which downward movement was slow and in which, immediately prior to Tongaporutuan time, shelf conditions prevailed. This geosyncline—the Eastern Geosyncline of Macpherson (1946)—was situated between two north-north-east trending anticlinal, submerged "highs", i.e., a western high through Otane and an eastern high through Kairakau Township.

Recent publications (Carozzi, 1952; Kopstein, 1954; Kuenen, 1948, 1951, 1953a, b; Kuenen and Carozzi, 1953; Kuenen and Migliorini, 1950; Kuenen and Menard, 1952) have thrown more light on the hitherto rather inexplicable phenomenon of layered rock sequences showing graded bedding. Kuenen's (Kuenen and Migliorini, 1950) experimental work on graded bedding and Migliorini's (op. cit.)

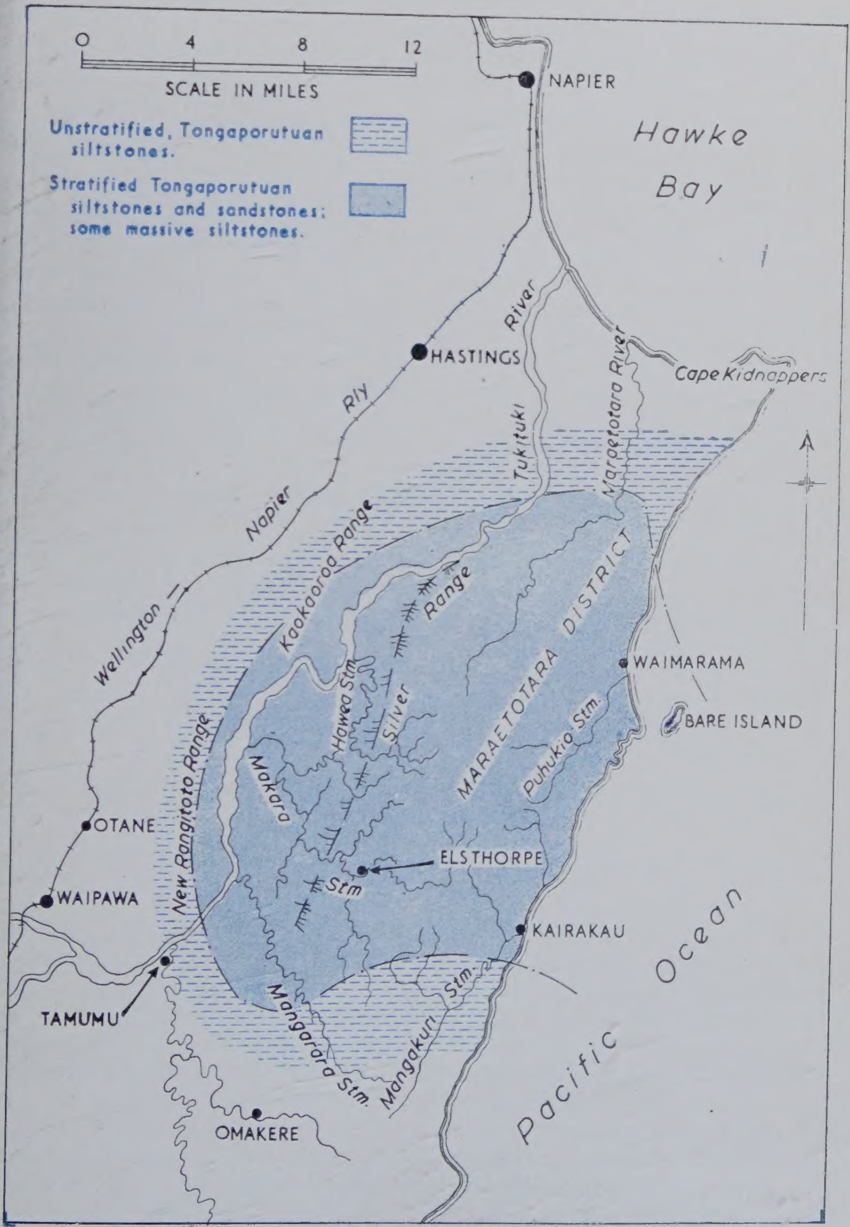

FIG. 3.—Distribution of Tongaporutuan strata.

fieldwork on banded strata in Italy have led to the development of a theory in which turbidity currents are accepted as the main transporting agents. This theory alters profoundly the value of such geological concepts as are implicit in the terms "littoral" and "neritic". It provides an explanation for the deposition of coarse-grained sediments over a much larger area than could formerly be accounted for.

The turbidity current theory was recently stressed by Cotton, 1951, as a very probable mechanism to explain the alternating beds in various parts of New Zealand, amongst others for those in the Miocene of the East Coast of the North Island. A careful study has been made of these beds, more or less with the above mentioned theory in mind. However attractive the turbidity current theory may be, it has been deduced that in Central Hawke's Bay a different system of deposition operated in Tongaporutuan times, a system that led to the development of a sedimentary sequence superficially similar to those strata presumably laid down by turbidity currents. It was impossible to detect the method of sedimentation of the Makara facies without extensive fieldwork on the distribution of individual sandstone bands; the investigation therefore developed into a regional survey embracing the entire Tongaporutuan sedimentation in Central Hawke's Bay

The information gathered from this study has been applied to the alternating sequences of pre-Tongaporutuan Tertiary strata and of the Mesozoic and Paleozoic greywackes. Much of the evidence for interpreting these older sequences is buried under younger rocks. But the details of bedding observed resemble those of the Tongaporutuan system so closely, that the writer believes they can be explained by the same mode of deposition as he postulates for the Tongaporutuan strata.

THE SEDIMENTS

The banded, graded Makara Facies has the following characteristics.

Thickness of Individual Beds

The thickness of these conformable beds veries greatly. Successive layers range in thickness from ½ in. to 10 ft and more. Beds up to 100 ft in thickness have been observed, but they are exceptional. The irregularity in thickness seems to be a common feature; beds of equal thickness have rarely been observed in succession. Laterally the thickness of each individual sandstone or siltstone band does not change appreciably over short distances, but over long distances (5 to 10 miles) the thickness does alter. The presence of the earlier mentioned tuffites and also marker-sandstone bands make it possible to trace individual sandstone bands over great distances. The sandstone bands have been found to be of greatest thickness in the area west of Elsthorpe Township that is roughly the area comprised by the 5000 ft isopach line (Fig. 23) and here for convenience is called the Makara district. Sandstone bands thicken towards this area, although the mode of thickening is rather different in different directions. From the Makara district northward and southward thinning is gradual, as shown in Fig. 4; the eastward thinning is far more abrupt (Fig. 5).

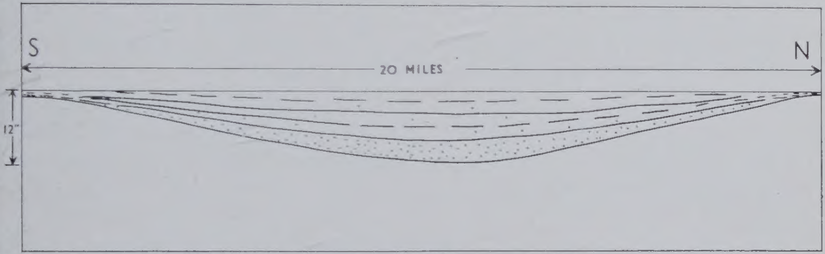

FIG. 4.—Profile of one sandstone band along strike (section B–B′, Fig. 22), showing gradual thinning towards south and north. Only major micro-bands illustrated.

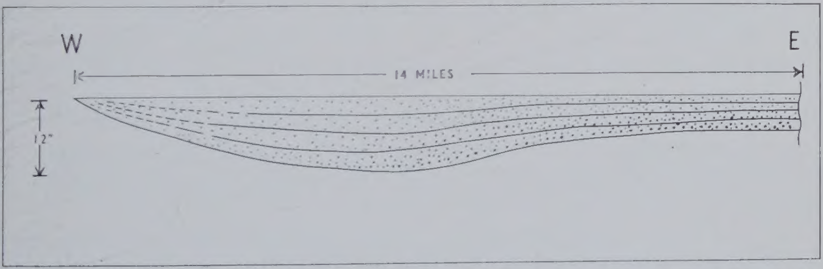

FIG. 5.—Profile of one sandstone band normal to strike (section A–A′, Fig. 22), showing coarser grade and abrupt thinning in eastern half. Only major micro-bands illustrated.

Although sandstone bands become thin and insignificant towards the northern and southern edges of the Makara facies, they have not been found to peter out inside that area. Eastward the thinning does not lead to fading out, on the contrary the sandstone bands become more clearly defined. The siltstone bands do not thin out to such an extent as the sandstones; they remain more or less equal in thickness throughout the area and merge into the massive siltstone facies.

Sandstone bands that are about one foot in the Makara district are only a few inches thick in the eastern part of the Makara facies. Only one sandstone, the Silver Range Sandstone, is more than 100 ft in the eastern part of the Makara facies and thins towards the Makara district. It can be traced for 20 miles along its strike (Fig. 3). An optical analysis (Mr J. J. Reed, pers. comm.) from this sandstone in the Kairakau area is as follows:

"The sand grains are considerably iron-stained; the stain was removed by dilute hydrochloric acid prior to micorscopical examination. The main constituents are quartz, alkali feldspar (orthoclase, albite-oligoclase), and composite grains in about equal proportions. Ferromagnesian minerals, dominantly chlorite though some biotite is also present, form about 5% of the sample. Other clastic minerals noted were rare epidote, sphene, and zeolites. The composite grains are largely greywacke fragments in which quartz is dominant. The grains are generally angular to subangular."

The thinner eastern sandstones, in contrast to those in the Makara district, are quite rich in smaller Foraminifera, mainly of the genera *Textularia, Robulus, Cibicides,* and *Nodosaria.* Some *Globigerinas* and *Orbulinas* have been noticed.

Grading

Although "dirty" throughout, every bed is clearly graded and consists of a sandy base and a silty-to-muddy top. True muds are present only in the uppermost parts of the silt layers. Such lutaceous horizons are conspicuously present in the western and northern parts of the area occupied by the Makara facies. The silts are usually blue-grey and the sandstones brownish, the difference in tint being due to differences in grain size, and therefore the result of weathering. Throughout the distribution area of the Makara facies the colour change takes place in the graded beds at that horizon where the largest common grain size is approximately 75 μ. "Largest common grain" is here defined as the size of the largest grains that make up a significant proportion (20 to 30%) of the sediment.

As well as vertical grading, horizontal grading is also apparent. The sands in the eastern part of the Makara facies are very much coarser than in the western part (Fig. 5), although the thicknesses of sandstone beds are less in the east than in the west. In all bands a westward decrease in grain size has been observed.

In a high proportion of outcrops the distinctive weathered profile (Fig. 6) of each sand-silt cycle provides further evidence of grading. This feature is particularly conspicuous in the western and northern parts of the Makara facies; in the eastern part coarser sands result in more abrupt grading, and profiles tend to become stepped (Fig. 7).

The banding observed in the field is usually described as alternating sandstone and siltstone bands, this description is, however, inadequate as it does not indicate the relation between the grain sizes of the two lithologies. In alternating beds of this type, a sand and the covering silt belong to one cycle.

Basal Shelly Layer

Occasional whole shells and shell debris, where present, are always confined to the very base of a sand layer, and are nowhere found

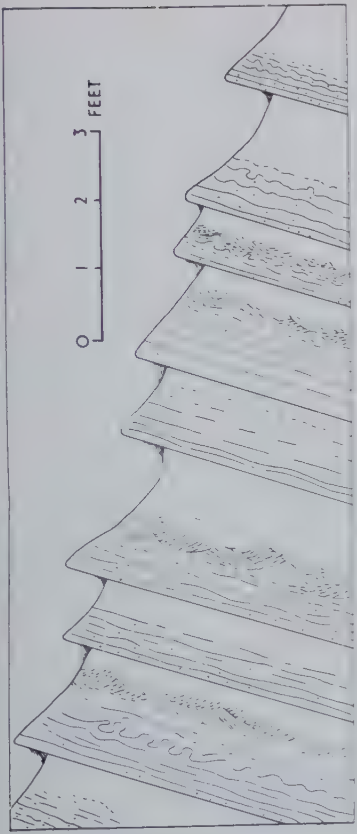

FIG. 6.—Profile of sandstone and siltstone beds, showing the effects of weathering and details of bedding. Drawn from outcrop at Hawea Stream.

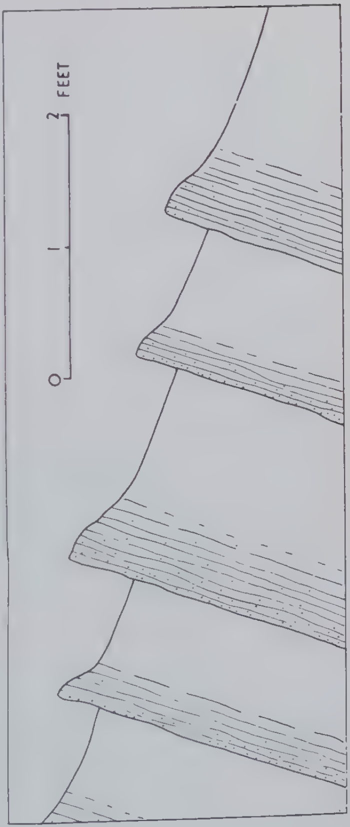

FIG. 7.—Profile of sandstone and siltstone beds, showing stepping between sandstones and overlying siltstones. Drawn from outcrop at Kairakau.

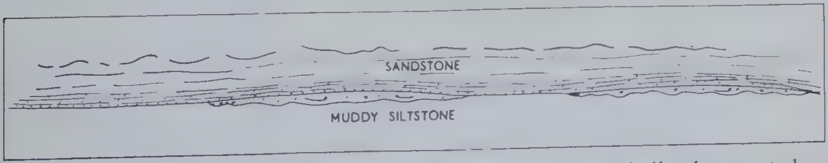

FIG. 8.—Cross-section through sandstone bands showing shelly layer at base of sandstone.

higher up in a bed. In beds more than 1 ft thick this basal layer often consists of a patchy, moderately hard and very calcareous band of shell fragments, rare small complete shells, and Foraminifera (Fig. 8). In all instances the coarseness is due to the shell material and not to an increase in grain size of the sand particles. The shelly layer is very irregular; it never exceeds a few inches in thickness and is separated from the overlying sands by a well-defined horizon. The sands immediately above this basal shelly layer are at most only slightly calcareous. The calcium carbonate content increases again in the siltstones, i.e., towards the top of the bed. Tests were made with a solution containing 10% hydrochloric acid.

Where the calcareous basal shelly layer is present, the surface of the underlying siltstone is ripple marked; where it is absent, the boundary between the silts and the sands at the base of the overlying bed is straight. These shelly layers are more common in the eastern part of the distribution of the Makara facies and occur in the western part only in the bases of the thicker sandstones. They are sometimes very resistant to erosion, causing minute waterfalls in streams, and giving outcrops a rugged appearance.

Micro-banding and Cross-bedding

On closer examination individual sandstone strata show micro-banding with beds $\frac{1}{20}$ in. to $\frac{1}{8}$ in. thick. The micro bands are not immediately obvious, but show up well in favourable light. Usually a certain amount of shading, for instance with a hat over the outcrop, gives the desired effect. Towards the upper part of the sandstone band the micro-banding is commonly disturbed by intrastratal crumpling, but the original micro-banding is still discernible. Micro-bandings are much better defined in the eastern part of the Makara facies than in the western part. In the eastern part they are clear and coarse grained and, where they crop out, individual micro-bands can be traced over several chains. In the western portion they are less sharp due to the greater muddiness of the sediments in general. A sandstone bed appears to have been built up by the deposition of one micro-band upon another (Figs 9 and 10).

The micro-bands become very vague on reaching the siltstone grade, streaks of indeterminable plant remains, which occur commonly, indicate the banding. Occasional cross-bedding occurs in this grade. Cross-bedding, if present, continues in the siltstones but fades towards the top, particularly in beds where the upper layers reach the mud grade and the sediments become very dense and massive. Cross-bedding (Fig. 6) occurs particularly in the northern part of the Makara facies and has not been observed in the eastern and southern parts. In Fig. 11, the micro-bandings in the basal part of the sandstone show that the filling of the depressions in the earlier deposited siltstones took place layer by layer. These depressions are either ripple marks, flow or scour channels. During sedimentation these depressions were filled and sedimentation took place on a more and more even surface. It is of importance to note that the sedimentation did not follow the micro relief.

Basal Sandstone Contact

A very sharp horizon separates the silts of one bed from the covering sands of the next bed, the type of boundary varying with the geo-

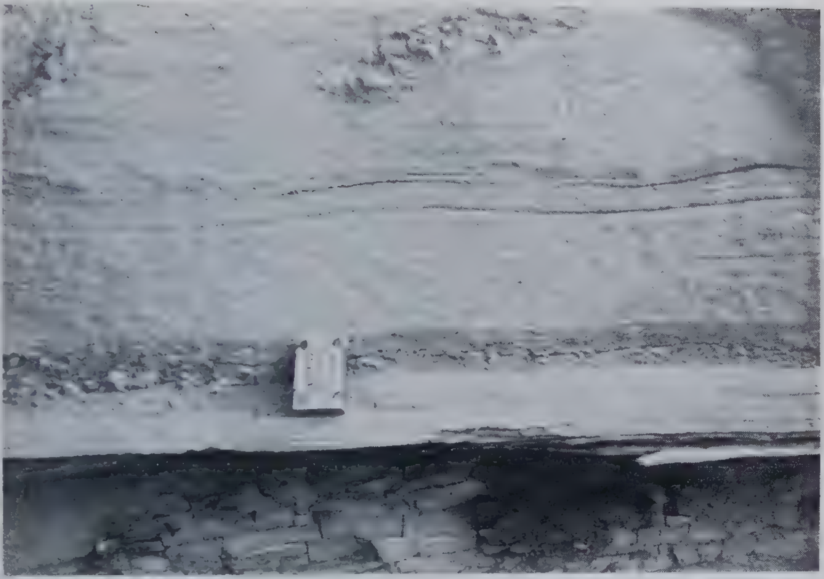

FIG. 9.—Micro-bedding in sandstone band, also showing sharp contact between sandstone and underlying siltstone.

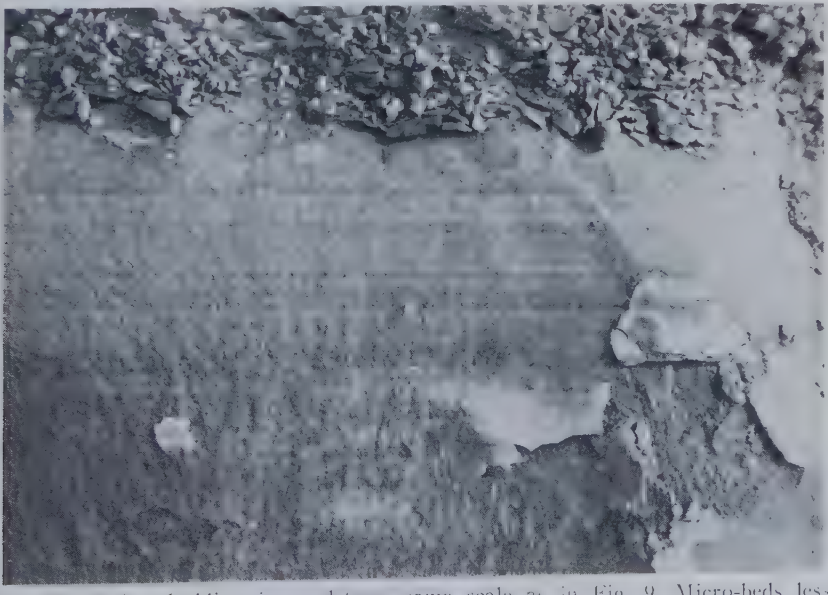

FIG. 10.—Micro-bedding in sandstone, same scale as in Fig. 9. Micro-beds less pronounced than in Fig. 9 because of finer grain size. Sandstone grading into siltstone at top. Sandstone breaking up grain by grain forming smooth surface, siltstone breaking up fragment-wise. Photograph from outcrop in Makara Stream.

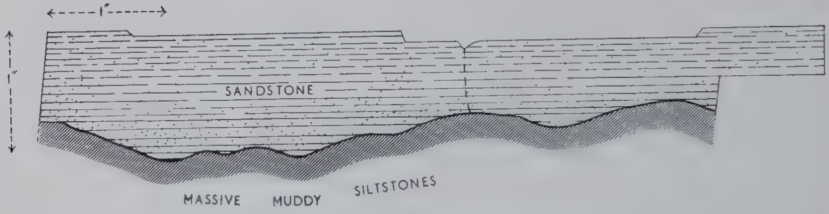

Fig. 11.—Micro-banding in sandstone. Filling of depressions in the earlier deposited muddy siltstone took place layer by layer until micro-relief was completely buried under continuous sheets of micro-bands. Drawn from hand specimen.

graphical position in the area of the Makara facies. Basal shelly layers are rather common in the eastern part of the distribution area of the Makara facies; they diminish westward and there the sands lie immediately on top of the silts apparently without much scouring, as the surface separating the sands from the silts is ripple marked. The marking is most highly developed in the northern and western part of the Makara facies.

Occasional curled flakes of mudstone are incorporated in the base of the sandstone, especially where the underlying siltstone is very muddy. Shallow, sheet-like sand bodies also occur in the upper part of the muds, as if sand had been pushed underneath a thin skin of mud (Fig. 8). The undersides of the sandstones occasionally exhibit flow markings, all orientated in a west-north-westerly direction (Fig. 12). The flow markings also depend on the geographical position in the Makara facies. They are well developed in the eastern and central parts of the Makara facies.

Another important feature is the appearance of borings in the top of the siltstones on the boundary between a siltstone and the overlying sandstone. Usually not longer than 1 in., and ⅓ in. or less in diameter, these borings invariably occur in the uppermost parts of the siltstone. They seem to have been formed during the initial stages of the sand sedimentation, as the borings continue into the lowest micro-bands of the sandstone.

Scour Casts

During the examination of the above mentioned borings, decisive evidence was obtained as to the development of scour casts. These develop immediately on the off-current side of the thrown-up material of the boring, the effect being similar to that observed when a pebble is laid in a shallow stream; the off-current side is excavated and a deep pit and channel formed behind the pebble. This depression is here called the scour pit and scour channel. The upthrown material of the boring acted in exactly the same manner as the pebble in the stream.

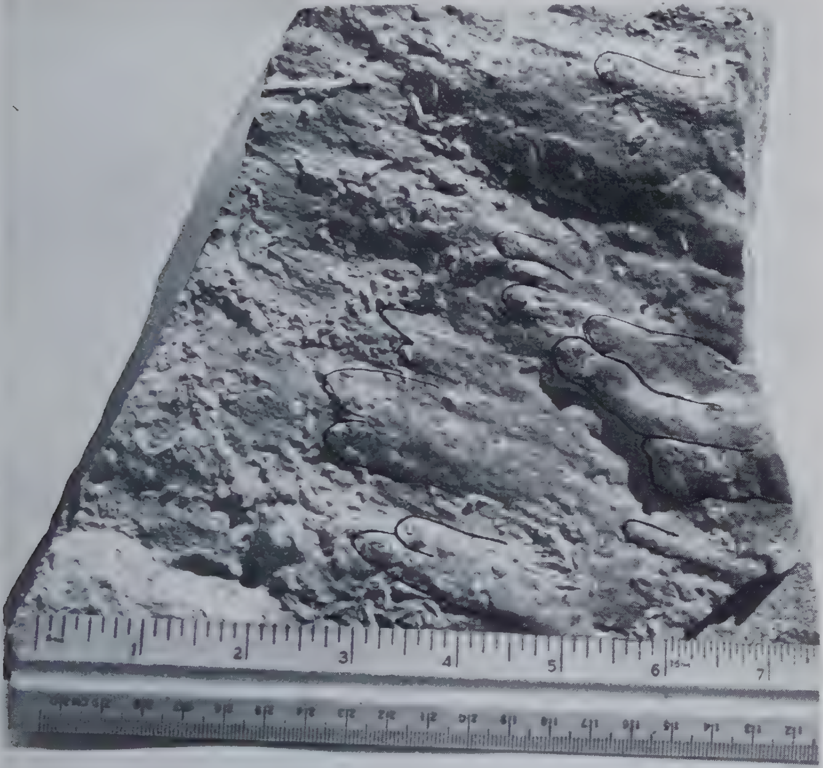

FIG. 12.—Scour casts on basal side of sandstone (casts outlined in black). Current flowed from south-east to north-west, i.e., from top left to low right. Specimen from Makara Stream, 2 miles west of Elsthorpe township.

With the succeeding deposition of micro-bands, the borer was overwhelmed, its upthrown material smoothed by the incoming sands and the scour pit and channel filled by the coarsest sand immediately behind the obstacle, and partly enveloping it. Under these conditions any obstacle, such as a boring, a shell fragment, or coarse sand grain, will give rise to a scour cast. Mr M. C. Pick (pers. comm.) has informed the author that he has seen a number of instances where scour casts have been initiated by an *Inoceramus* shell fragment.

The scour casts are clear and sharply pointed in the eastern part of the Makara facies, become blunt and irregular in the central part and are absent in the western and northern parts of the Makara facies, where they are apparently replaced by ripple-marking. Scour casts also occur in various layers, but always in the very bottom of a sandstone bed. The various stadia in the development of the scour casts are depicted in Fig. 13.

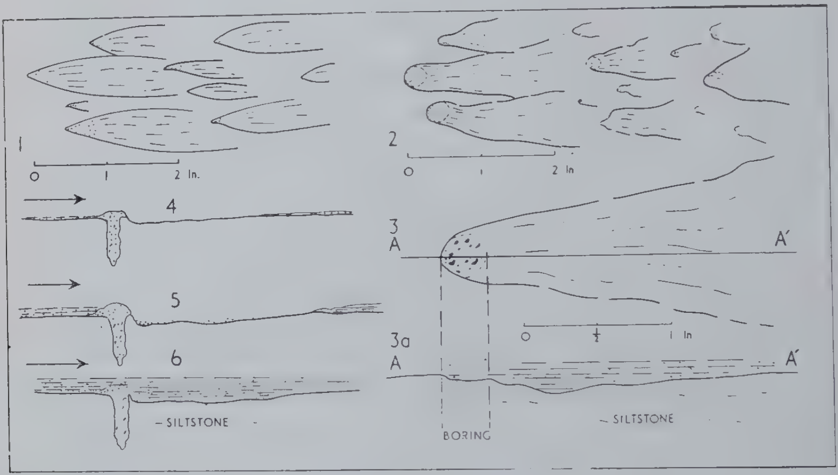

FIG. 13.—Scour casts. 1 and 2, different types of scour casts; 3, scour cast magnified; 3a, scour cast in section; 4, 5, and 6, stages in development of scour casts.

Crumpled Strata

Small-scale intrastratal crumpling is commonly observed in individual beds. Usually a system of minute anticlines and synclines, with a wave height and a wave length of a few inches only, has been developed, at least when judged by the appearance of vertical sections in outcrops. The anticlinal ridges are commonly overturned and their crests are in some cases truncated by erosion planes, in others stretching of micro-beds has taken place before the deposition of the overlying micro-bands (Figs 14, 15). The erosion planes are very limited in extent and are only traceable over a few feet.

This type of crumbling is confined to the middle section of a cycle and always occurs in sands with a largest common grain size of 100 to 150 μ (Figs 14, 15). When these anticlines and synclines are examined more closely either by small-scale excavation or where segments of alternating strata are exposed, as for instance in stream bends, they appear to have no consistent arrangement of anticlinal and synclinal axes; they appear to be a system of minute domes and basins, which in cross-section on the surface of the outcrop give the anticlinal-synclinal picture. The direction of the overfolding in the commonly occurring, overturned, anticlinal crests is not consistent.

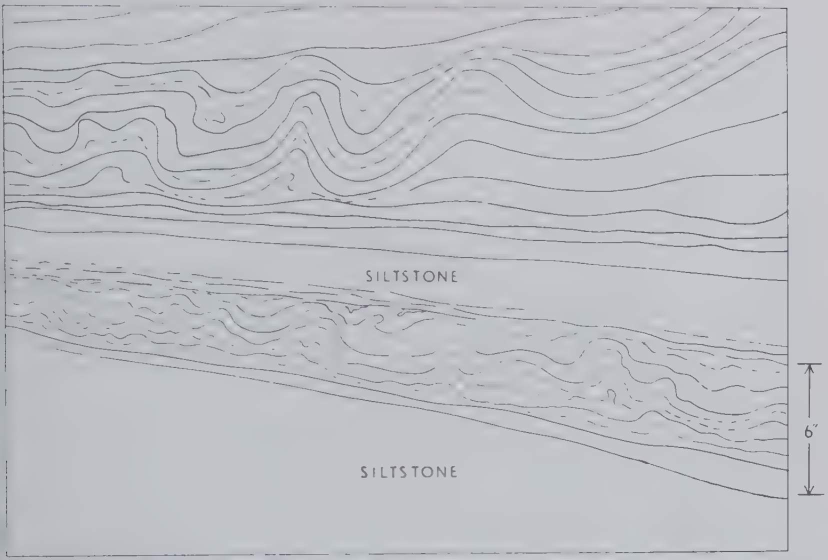

FIG. 14.—Crumpled bedding in sandstones in Hawea Stream. Drawn from photograph. Only major micro-bands illustrated.

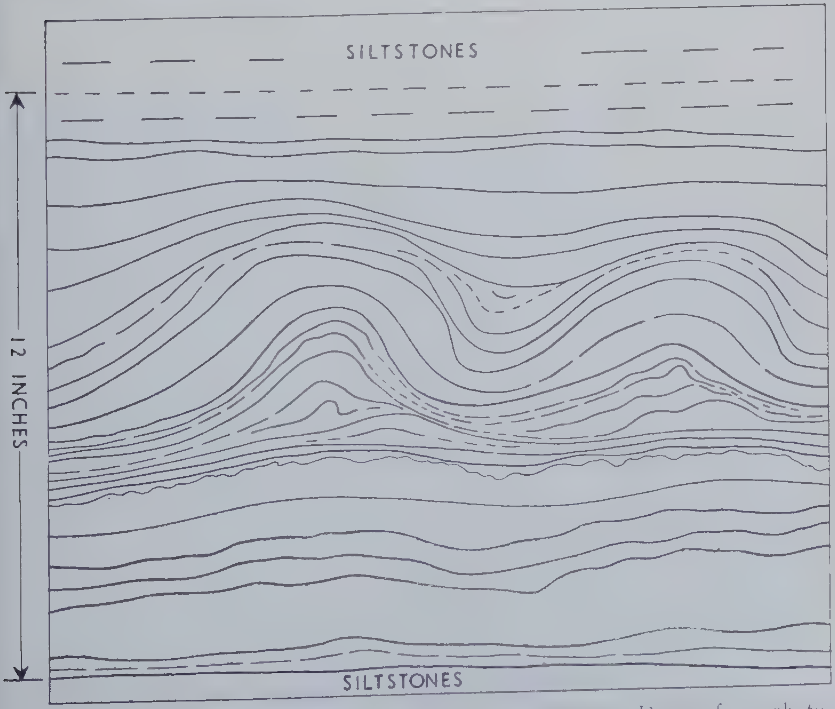

FIG. 15.—Crumpled bedding in sandstones in Makara Stream. Drawn from photograph. Only major micro-bands illustrated.

This type of crumpling is one of the features most difficult to explain, but taking into consideration that only a certain range of grain sizes is involved and that no sliding of the crumpled strata has taken place, the crumpling seems to be a result of compaction—a compaction probably from a watery, quicksand-like mixture. The slope on which this compaction and consequent crumpling took place cannot have been steep, as then slumping should have taken place.

Slumping

Large-scale slumping, affecting more than one cycle has occasionally been observed. This type of slumping does not, however, influence the internal grading of a cycle. The results of such slumps have been seen only in section and their lateral extent has never been observed. The distance over which a slump travelled is usually not more than a chain. Above such a slump the conformable sequence continues.

Slumping that did influence the lithology of a bed has been seen in one locality (grid ref. N141/297845) and may best be described as an underwater lahar. No sorting took place; large blocks are incorporated in a muddy matrix (Fig. 16). The fact that these blocks did not sink to the bottom of the lahar suggest that the lahar had a very high viscosity. The blocks, recognized on lithology, are of Maestrichtian age and are part of the sequence that occurs further east in the

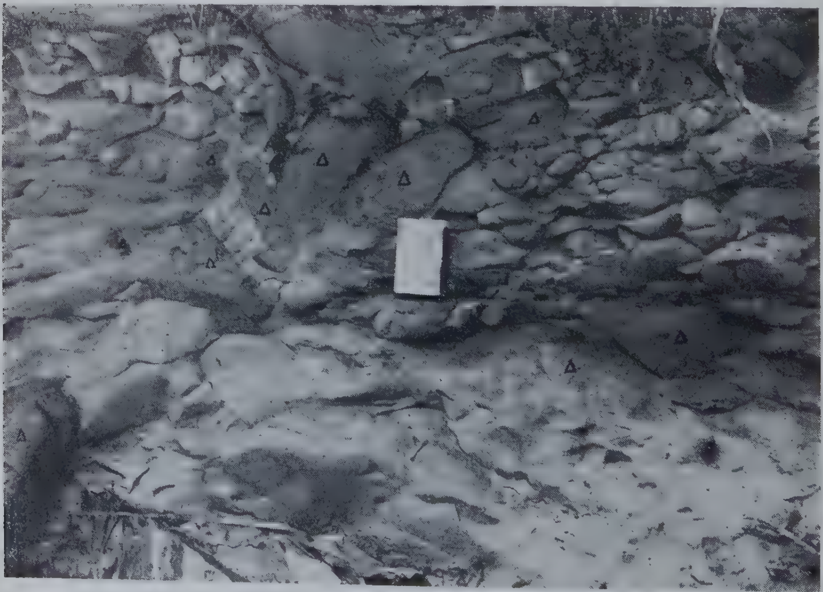

FIG. 16.—Massive siltstone with blocks of older strata scattered throughout the bed. Older blocks are indicated by black triangles.

Kairakau area. The thickness of the lahar is only 3 to 4 ft, its lateral distribution is unknown. Resting on the lahar is micro-banded sandstone in which the basal bands are clearly seen to be disrupted in between the blocks of the rough lahar surface (Fig. 17).

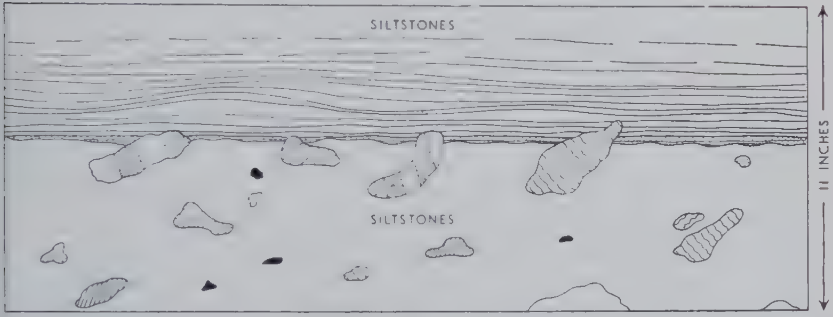

FIG. 17.—Massive siltstone, with blocks of older strata, overlain by micro-banded sandstone. Note micro-bands between blocks, indicating that sands were deposited on rough surface.

Sand-Silt Ratio in Individual Beds

Throughout the Makara facies the individual beds vary widely, not only in thickness but also in sandstone-siltstone ratio. In one cycle sand may occupy 50% of the thickness, in the overlying one it may only occuply 10%. Sands may occupy between 10 and 90% of the thickness of a cycle. Both sandstones and siltstones are moderately soft and disintegrate readily. Although the siltstones appear to be tougher than the more friable and porous sandstones in the hand specimen, they are less resistant to weathering. The sandstones are less rapidly eroded than the siltstones, hence the profile in outcrops. (Fig. 6).

Mudstone Flakes in Sandstone

Mud flakes are present locally in the very basal portion of the non-calcareous sandstones. They are very fine-grained in texture. Their sharp edges indicate that they have not been transported over any distance. The edges are frequently curled as if derived from sun-cracked mud layers.

The Siltstones

The siltstones in the banded sequence become increasingly calcareous and fine-grained towards the top. Smaller Foraminifera, almost absent in the sands, are common in the silts, particularly in the more muddy facies. Where the shelly horizon is present at the base of the overlying sand the ripple marking on the top surface of the silts is preserved. Above the colour change, grain size decreases gradually and the deposit is very similar to the shelf siltstones.

The siltstones outside the area occupied by the Makara facies may be termed shelf siltstones, they are massive and characterless. Approximately 70% of the grains are smaller than 25 μ, while in the remaining 30% the grain size ranges from 25 to 75 μ. Occasional whole shells and shell debris lie scattered through the deposit.

General

In the banded upper Miocene succession of Central Hawke's Bay, each bed comprises a sandy and a silty part. Whatever the ratio between a sand and a silt, the bed is always graded. One band may show grading as well as cross-bedding. The sandstone parts commonly show micro-layering. The decrease in grain size towards the top of each cycle indicates that the supply of coarse material was gradually pinched off and increasingly finer sediments were deposited, until a new cycle began. Cross-bedding at the base of the siltstones indicates that ripple-marked surfaces were developed on the silts during the period of their deposition.

GRAIN SIZE ANALYSIS

Approximately 200 samples were collected for simple re-deposition tests, to determine their sand, silt, and mud contents. Samples were collected from a large number of localities (see sample localities, Fig. 18), not only from both banded and massive facies, but also from the base as well as from the top of sandstone beds. Between 400 and 500 g of each sample was crushed, and placed in glass containers with ample water. After a severe stirring the sediment was allowed to settle. All showed a marked grading. The silt-mud-sand ratios differed considerably with geographic location. The grading in the tests was much more perfect than that in the field. Moreover, when the artificial sediment was allowed to consolidate for a few days, it was exceedingly difficult to get it into suspension again and severe stirring was necessary.

From these tests it was clear that the silt-mud content increased from the base to the top in one band, as the grain size decreased. In the base of a sandstone band the silt-mud content is very small, but increases towards the top. The amount of silt-mud, however, varied systematically from locality to locality. Comparison of samples from the same horizon in the cycle and different localities showed that the amount of silt-mud increased in proportion to the distance of the sample from the south-eastern part of the distribution area of the Makara facies (Fig. 18).

In the base of the Silver Range sandstone the silt-mud content is 10% at Kairakau, 15% at Elsthorpe, and 20% at Grunard, points A, B, and C respectively in Fig. 18. The "largest common grain" size

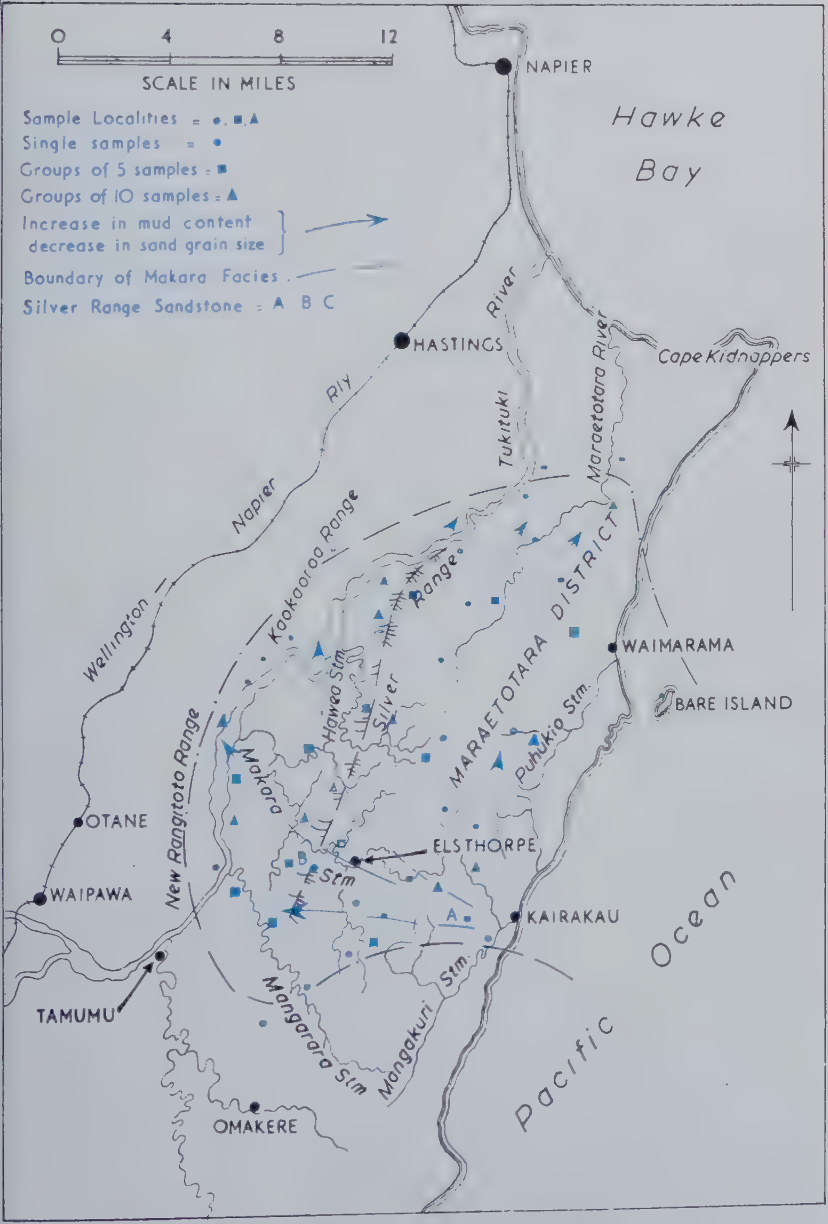

FIG. 18.—Sample localities in and outside Makara facies area, showing directions of decrease of grain size in sandstones.

in the base of the Silver Range sandstone is 450 μ at point A, 375 μ at B, and 275 μ at C. The Silver Range sandstone is thus graded in a horizontal as well as in a vertical sense away from Kairakau.

The best vertical grading may be observed on relatively thin cycles in the Makara district, in which approximately 50% of the thickness is sandstone. In very thick sandstone beds, the sand decreases to a certain grain size from the base of the sandstone upward and maintains this grain size before it commences to grade into the silts and finally into the muds if these are present.

The large grains in the Kairakau area are not entirely fragments of quartz or rock but include smaller Foraminifera. These Foraminifera apparently lived there during the deposition of the sandstone beds because mostly benthonic genera have been found.

Another question investigated was whether there was any relationship between the thickness of a sandstone band and its initial grain size. Fifty-six samples from the earlier-mentioned 200 were selected from the localities 1 to 7 (Fig. 19), they were all taken from the base of sandstone bands, that is from the coarsest fraction in the graded sequence. Precision in the measurement of grain sizes and shapes is time consuming and requires more facilities than were available for this reconnaissance field study. The samples were washed, mounted on a microscope slide and quick measurements were taken with an ocular micrometer of the greatest diameter of the largest grains that made up a significant proportion of the sand. Occasionally there were a few grains of much greater diameter and of more uneven shape than those that determined the coarseness or character of the sand as a whole, and they were not measured. The results were plotted on ordinary rectangular graphs and are shown in Fig. 20. The general finding is that the thickness of a sand is definitely related to the grain size in its base. The samples from localities 1, 2, 3, and 5 are from approximately the same horizon, those from localities 4, 6, and 7 are from a higher horizon. In addition to demonstrating the relationship between thickness and grain size, these results also show the marked horizontal grading in a direction away from Kairakau (Fig. 18).

MAKARA BASIN

Cross-sections (Figs 21 and 22) based on plentiful dips and strikes through the area covered by the Makara facies show that the banded sediments reach a much greater thickness than the massive facies. The isopach map (Fig. 23) has been constructed from observed thicknesses.

The isopachs and the cross-sections of the Tongaporutuan sediments show that the banded sequences were deposited in a basin of limited extent, here called the Makara Basin. In this basin most of the history of the filling of the geosyncline is recorded on a small scale. The outline of the Makara Basin may readily be deduced from

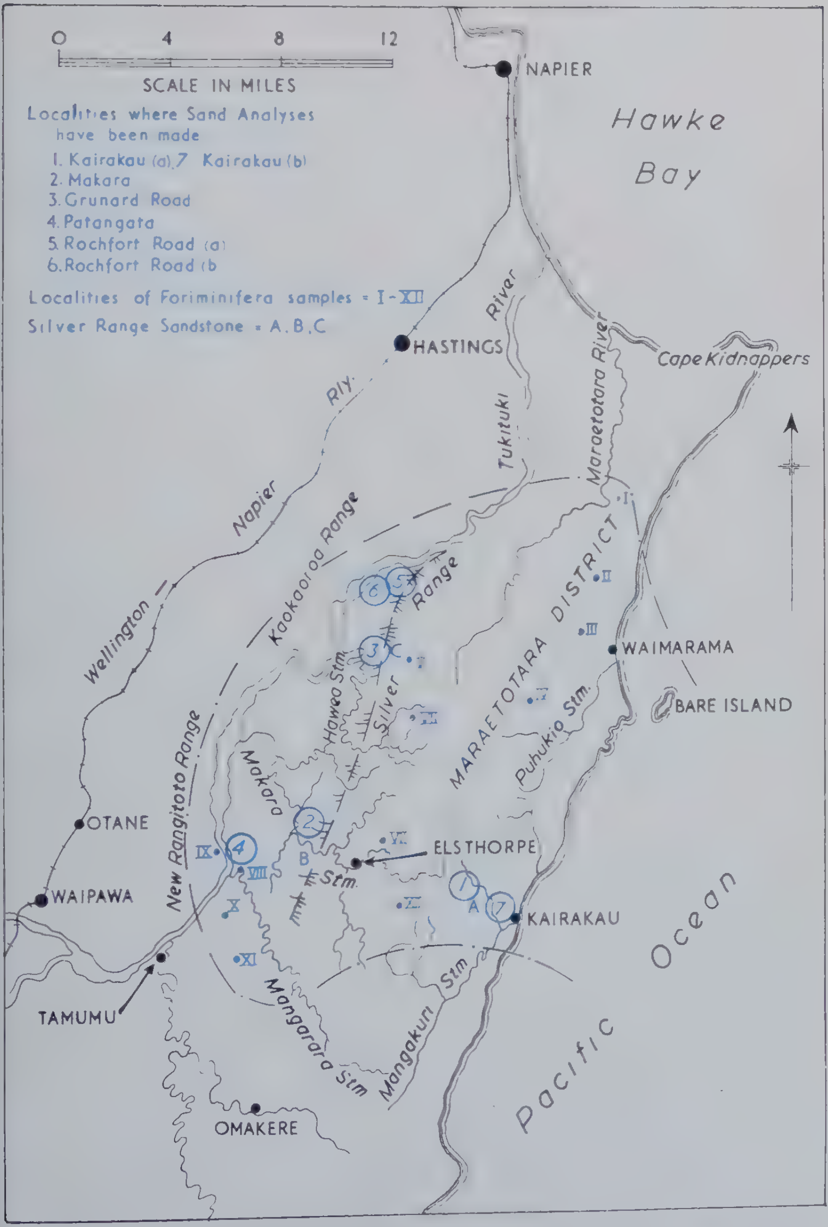

FIG. 19.—Outline of Makara Basin, showing samples localities as in Fig. 20, and Foraminifera samples.

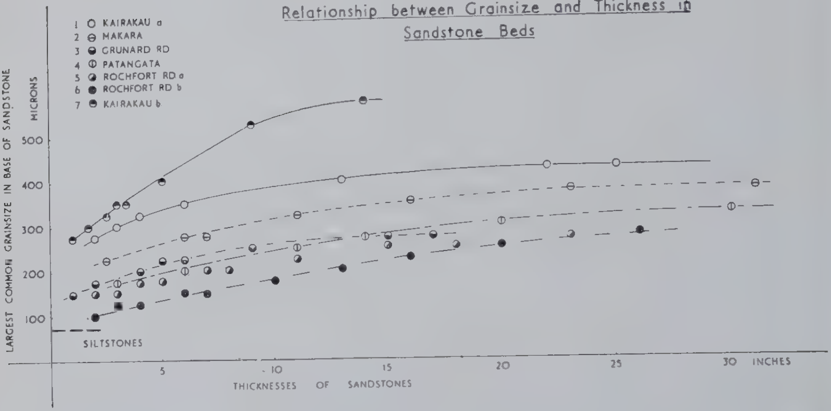

FIG. 20.—Graph showing relationship between grain size in base, and thickness of sandstone beds.

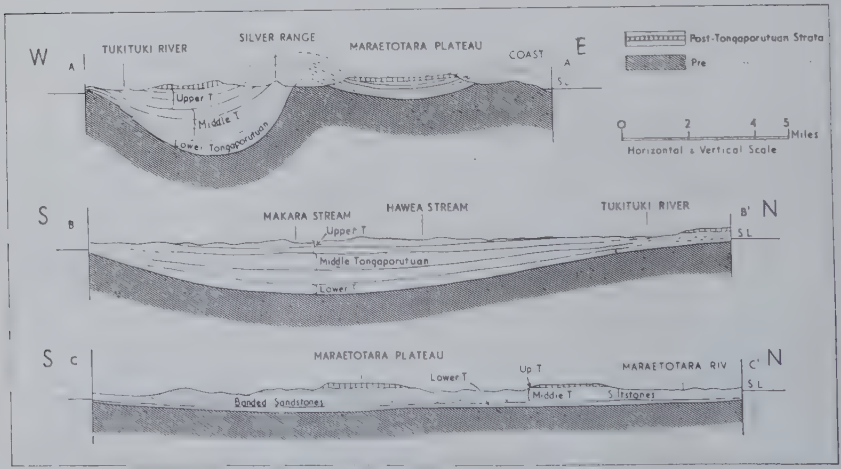

FIG. 21.—Cross-sections through Makara Basin, showing present-day folding. Faulting not shown. See Fig. 22.

the pattern of the isopach lines and from the cross-sections. It was approximately 20 miles long and 8 miles wide, and was aligned in a north-easterly direction.

During Tongaporutuan time sedimentation was much faster inside the basin than outside, where the pre-Tongaporutuan shelf conditions continued into Tongaporutuan times. Makara Basin, located well within the Eastern Geosyncline, was thus a small feature, having all the characteristics of a true geosyncline except size. It was a local

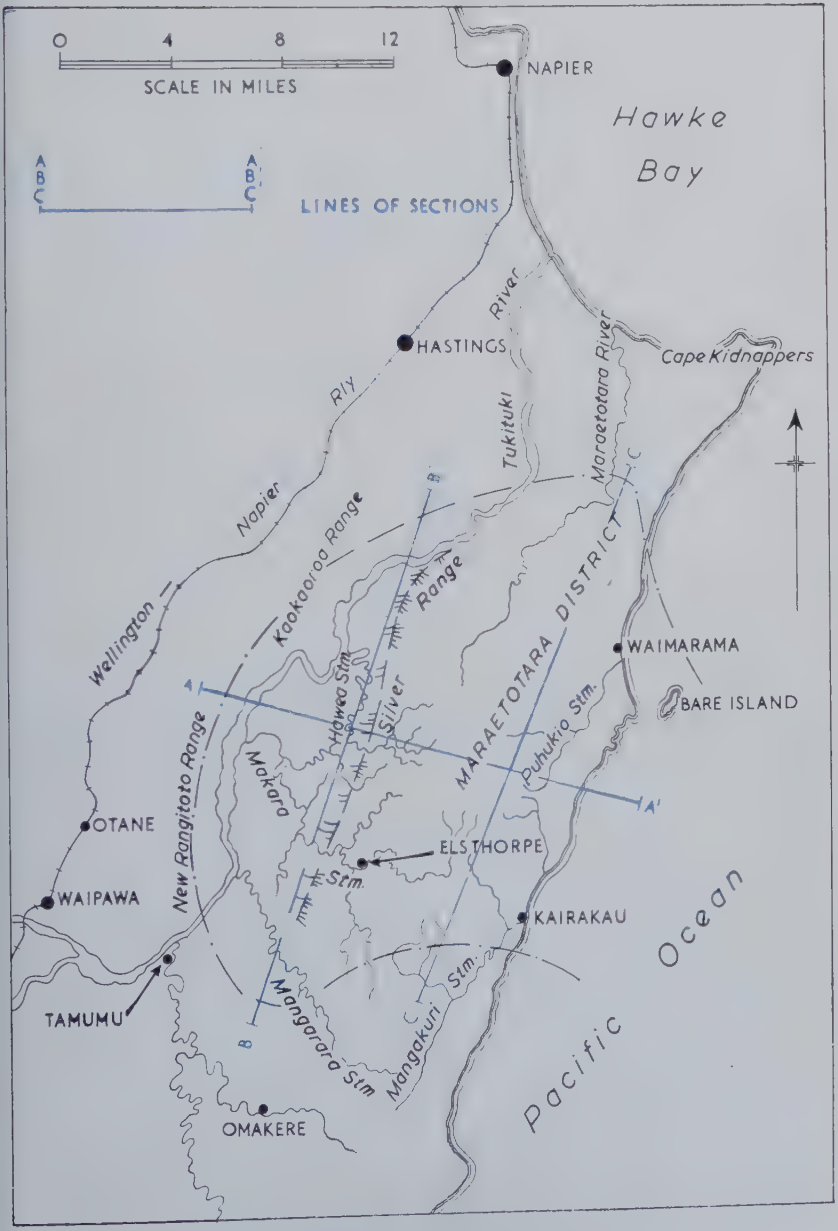

FIG. 22.—Locations of cross-sections.

deepening in a larger geosyncline, and the term "Geosynclinette" for this type of basin is here proposed.

The district to the west of the Makara Basin was structually high throughout the Oligocene and Miocene, forming the western limit of the Eastern Geosyncline. A shelf separated the Makara Basin from the open sea to the east. This eastern high, the eastern limit of Macpherson's (1946) Geosyncline, acted as a bar or threshold between the Makara Basin and the open sea. The name Kairakau Bar has been chosen for this threshold, which was lowest to the south-east of the Makara Basin. It is believed that the basin was filled mainly through this sag, and it is here that the coarsest sediments have been found. The profile C–C′ (Fig. 21) shows that the banded sandstones persist in the southern part of the Kairakau Bar. The cross-section A–A′ (Fig. 21) has been straightened and is shown in Fig. 24 to depict its outline before deformation of the area in post-Tongaporutuan time took place. It is of interest to note that the basal layers of the banded sediments in the Makara Basin already had an appreciable westerly dip before deformation took place, and that the dips at present exhibited by the Tongaporutuan strata are only partly due to orogenic folding movements.

SEDIMENTATION

Before discussing sedimentation it is important to determine the direction from which the sediments were derived and the nature of the downward movement in the basin. The decrease in grain size to the west indicates that sediment was derived from the east. There is, however, no evidence that a land mass east of Kairakau was being eroded in Tongaporutuan time to supply the necessary sediments. It seems more logical to assume that the materials were brought by sea currents, that flowed along the Tongaporutuan shelf, in a northerly direction, an assumption supported by the increase in mud content in a northerly direction (Fig. 18).

The subsidence of the Makara Basin may have been either continuous or intermittent, as a series of pulses. Intermittent movement seems the most reasonable to assume and also that the pulses were of irregular intensity.

On first consideration, some of the facts mentioned above seem to fit Kuenen's theory that the sediments derived by erosion from the adjacent land collected along the land margin and from time to time a turbidity current was initiated that whirled the sediment to greater depth. However, if the theory of turbidity currents as transporting agents, is accepted, every cycle in the sequence must be considered as the result of one turbidity current discharge. As conditions on land alter slowly, it may be presumed that the ratio between sand and silt deposited along the shore alters slowly accordingly. Hence the turbidity currents would draw from a deposit that changes very slowly in com-

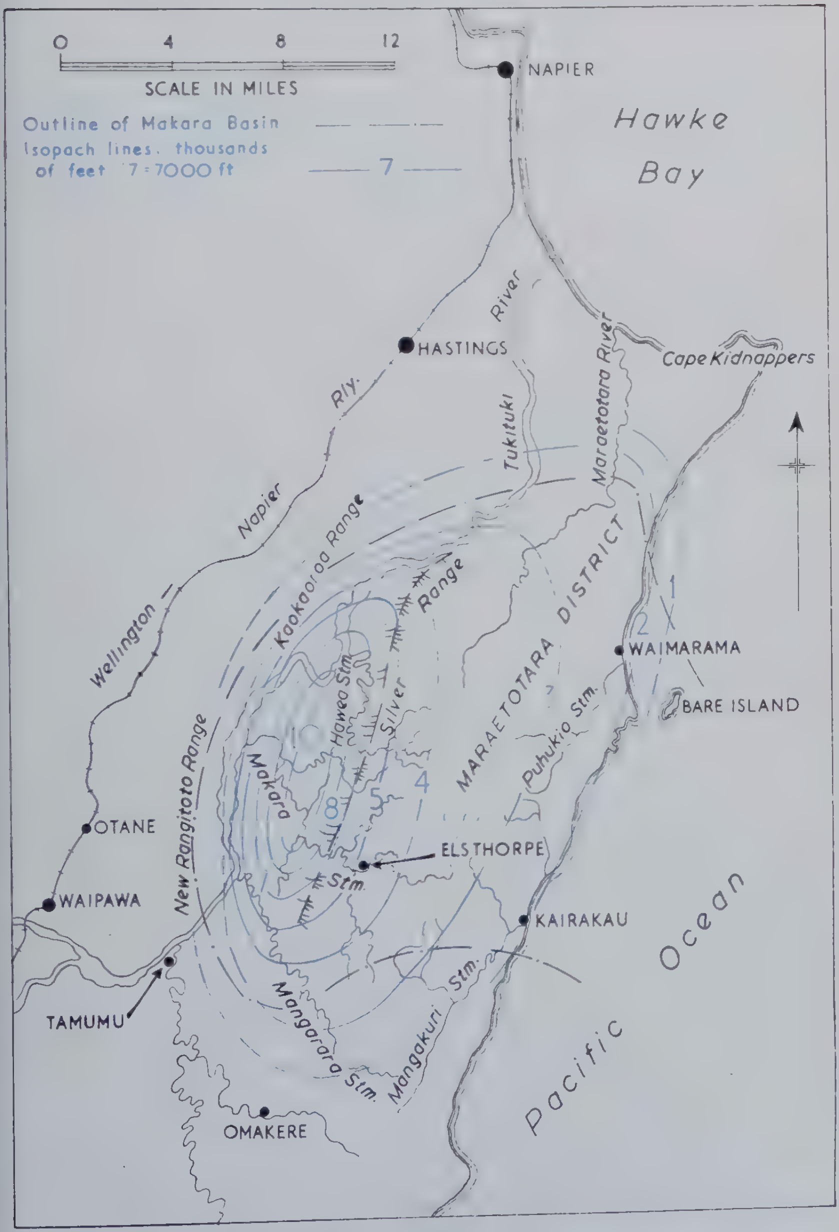

FIG. 23.—Outline of Makara Basin and isopaches for the Tongaporutuan strata.

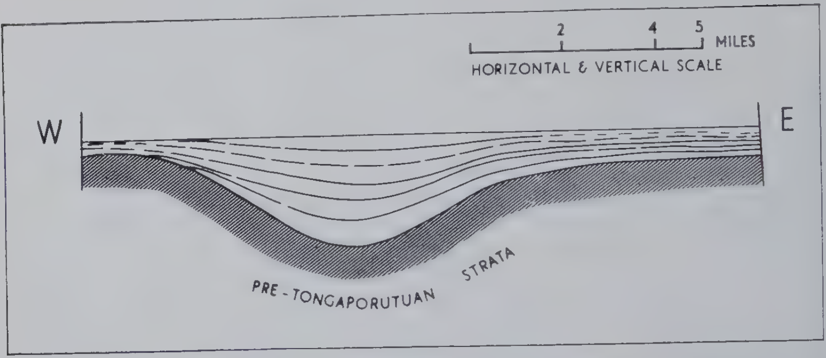

FIG. 24.—Section A–A′, Fig. 21, straightened to obtain outline of Makara Basin prior to regional folding. Note steep initial dips before deformation of area.

position and consequently the ratio between sands and silts should remain balanced in successive layers.

This is contrary to field evidence, which provides no reasonably regular sandstone-siltstone ratios in successive bands. A closer inspection of the data moreover reveals a number of facts that are exceedingly difficult to reconcile with the turbidity current theory; in fact they show something quite different. Deposition obviously took place in a shallow sea. The widespread distribution of cross-bedded sediments indicates that this shallow sea must have been of fair extent, and consequently there was not sufficient slope in the sea bottom to cause movement under the influence of gravity, earthquake, great storms, etc., that would initiate a turbidity current.

The grading obtained in the artificial sediments is much more perfect than in the natural sediment and developed spontaneously. Why then, has this not taken place in the natural sediment if it was deposited instantaneously from a turbidity current? The irregular basal calcareous horizon, micro-banding and the cross-bedding, the Foraminifera and the streaks of plant remains in the silts, the difference in calcium content, also show that deposition was not instantaneous and that a sandstone-siltstone cycle was the result of deposition over an appreciable time. These facts do not accord with the turbidity current theory.

The pre-Tongaporutuan strata indicate that before the Makara Basin came into existence, sediments were laid down on a shelf, as a thin and relatively even sedimentary sequence. In lower Tongaporutuan time these shelf conditions were maintained, resulting in a much wider distribution of the sandstones in that time interval than in middle or upper Tongaporutuan times, compare C–C′ (Fig. 21). After the lower Tongaporutuan sequence was deposited, the Makara Basin came into existence on the shelf, shut off from the open sea by the Kairakau Bar. During Tongaporutuan time detrital material, pre-

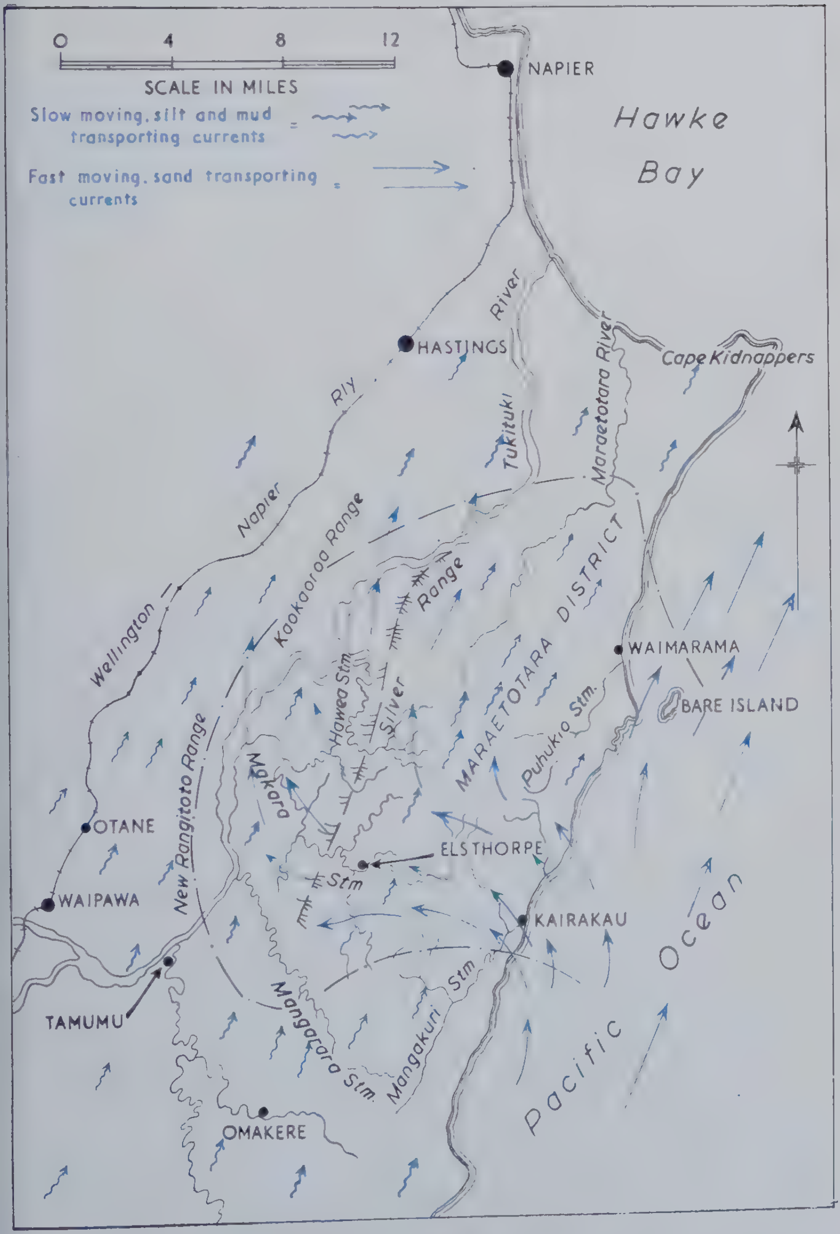

FIG. 25.—Paleo-oceanographic interpretation of current pattern in Central-Hawke's Bay during Tongaporutuan time.

dominantly quartz, was carried northward by sea currents along the edge of the Tongaporutuan shelf. Fine and coarse sediments were carried up by these currents (Fig. 25). There have apparently been two types of current, (1) a slow-moving, constant current that deposited fine, silty-muddy material continuously, and (2) a much faster-moving current that invaded the shelf area only under certain conditions and which, after its energy had been dissipated, mingled with the shelf currents.

Downward movements on the Kairakau Bar and in the Makara Basin varied the nature of the threshold. If downward movement was intermittent, as is presumed, the inward flow from the off-shelf currents would have been irregular. When the bar was suddenly lowered, the incoming off-shelf currents started to bring coarse material into the Makara Basin. Muds and silts were carried furthest into the basin, that is into the northern and western parts. The bulk of the coarse sediment was thrown into the Makara Basin across the southern part of the Kairakau Bar, where scouring must have taken place. Opposite this gap the bottoms of the sandstone layer show evidence of scouring (Fig. 12). Thus the banded strata in the western and northern parts of the basin are much more muddy than in the east. The incoming currents spread the sands over the entire basin in very thin layers, resulting in micro-banding.

The thickness of a sandstone bed, i.e., a sequence of micro-bands, gives an indication of the amount of downward movement during each pulse. After every movement the bar was lowered and sands entered the basin until it became too shallow for the passage of currents capable of transporting sand, and silts and muds alone were carried in, i.e., the normal shelf sedimentation continued.

Sequences in which sand beds are absent indicate times of very slow continuous downward movement, when the depth of the bar did not increase sufficiently to allow currents to carry in sands. Beds of thick sands indicate rapid downward movement both on the bar and in the basin. At the edges of the basin the sediments show very irregular banding; the strata comprise massive siltstones with rare sandstone beds. The sands of such solitary bands were probably carried in after the larger pulses, which must have had a widespread effect. The great variation in the thickness of the beds and in the percentage of sand in every bed is thus readily accounted for. In fact regularity would be very difficult to explain. After each phase of sand deposition the basin received deposits of silt and mud, and was colonised by Foraminifera and other benthonic organisms, conditions for their existence being suitable. The occurrence of smaller Foraminifera in the thin sandstones at Kairakau indicates that the sand deposition was not sufficient to suppress foraminiferal life. The currents were apparently adequate to keep benthonic life from being buried, as the smaller sand grains were only in transit to the Makara Basin. Pelagic forms such as *Globigerina* and *Orbulina* reached the basin and are found occasionally in the sandstones.

The basal, shelly layers of some sandstone beds were deposited immediately before sands started to invade the basin. In the western portion of the basin they have been found only at the bases of the thicker sandstones and, by the hypothesis set forth above, were deposited only after appreciable downward movement. Apparently the shell debris was transported by the strong, initial currents. The deposition of shell debris was highly irregular and the layers tended to be less patchy in the east than in the west. The irregular deposits are found in the western part where they are most clearly shown as micro-banded strata in depressions of a ripple-marked surface. In places where shell debris accumulated, the underlying ripple marks were preserved. Where this protective layer was absent, the ripple markings were destroyed by scouring of the invading, sand-laden currents. This feature is evident immediately opposite the gap in the Kairakau Bar.

The basin was filled spasmodically; the deposition of the sands was not instantaneous, but rather a slow process of building up micro-layer by micro-layer. The entire system of alternating beds was developed solely by current action. The deposition of the sands was more rapid than the deposition of the silty facies. The writer postulates deposition of the Tongaporutuan strata under very shallow conditions, with mud flats along parts of the shelf surrounding the Makara Basin. The discovery of seeds of the primitive New Zealand coconut, *Cocos zeylandica* Berry, in shallow sediments of immediately pre-Tongaporutuan age (Mr. D. R. McQueen, pers. comm.) indicate that land cannot have been far away.

Sedimentation features have been revealed with great clarity by the field data, the mapping and interpretation of which have enabled reconstruction of a complete sedimentation system in Tongaporutuan times in Central Hawke's Bay.

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GEOLOGY OF THE HARPER AND AVOCA RIVER VALLEYS, MID-CANTERBURY, NEW ZEALAND

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Summary

Soft Tertiary sandstone, mudstone, and conglomerate are preserved in a narrow strip parallel to the Harper Fault, within indurated sandstone and mudstone probably Triassic in age on the east flank of the Southern Alps. The structure of the Tertiary rocks is interpreted principally in terms of mid-Tertiary and late-Tertiary folding, to which some of the complexities of the basement structure are also attributed. Valley deposits and valley form are interpreted as the result of two ice advances during the Last Glaciation.

Introduction

The Harper River catchment is bounded by the Birdwood Range to the west, the Black Range to the north, and the Craigieburn Range to the east. Harper River, rising near Lagoon Saddle, and Hamilton Creek, rising near Cass Saddle, unite to form the south-west-flowing main Harper River, which is joined six miles below the junction of branches by the Avoca River; about five miles below this junction it flows into the Wilberforce River. The Avoca, though nominally a tributary of the Harper, is the larger river. The Birdwood Range forms the watershed between the Avoca and Wilberforce rivers; the Black and Craigieburn ranges form the watershed between the Harper and Waimakariri rivers.

The Harper and Avoca gravel flood-plains are up to half a mile wide, but except after heavy rain the rivers flow in braided channels which are easily crossed on foot. Peaks on the Harper watershed average nearly 6,000 ft, and form steep slopes broken in their lower parts by narrow terraces. Erosion is proceeding rapidly; shingle slides, aggravated by depletion of tussock cover on the higher slopes, have given rise to huge fans at tributary mouths. Beech forest (*Nothofagus cliffortioides*) clothes part of the area; in many of the more accessible parts it has been destroyed by burning.

Haast (1866, 1879) examined the Avoca River to its head and briefly described the basement rocks; Speight (1917) recorded Tertiary beds in the Harper River and described structural and physiographic de-

N.Z.J. Geol. Geophys. 1: 31–46.

velopment, noting that the south-west stretch of the Harper Valley is developed along a major fault-line. Packard (1947), in a geographical survey, briefly mentioned the physiography and the presence of fault zones. During brief visits in August 1948 and January 1950, Dr M. Gage and Dr H. W. Wellman collected fossils from the Tertiary beds.

The writers spent eight days in the area in autumn 1955. The nearest road reaches the Harper River four miles downstream from the Harper-Avoca junction. Three of the musterers' huts—Fitzwilliam Hut, one mile up the Avoca River, Triangle Hut, five miles up the Avoca River, and Harper Hut, four miles up the Harper River from its junction with the Avoca—were used during the visit.

Traverses were made up the Harper Valley to four miles above the junction of the Harper and Avoca rivers, and one mile and a half up Hamilton Creek, and a short distance up small east bank tributaries as far as the Harper Fault. The lowest 10 miles of the Avoca Valley and its tributaries were examined, and also Amphitheatre Creek, Centre Creek, and Lilian Creek. Field mapping in the valleys has been supplemented by determination of strikes from air photographs.

TRIASSIC(?) ROCKS

Distribution

Rocks probably of Triassic age crop out everywhere except near the main rivers, where they are covered by Recent flood-plain gravels, by Pleistocene gravels of the higher terraces, and by a narrow strip of Tertiary beds along the Harper River.

Content

Most of the rocks are of the normal Alpine facies of highly indurated rocks ranging from sandstone (greywacke) to mudstone (argillite). No systematic variation in content was recognized to help in elucidating structure or stratigraphy. Sandstone predominates over mudstone in most parts of the area, in places forming belts up to a quarter of a mile wide with negligible thicknesses of mudstone. A thick belt of finer rock was observed only in the Avoca River immediately upstream from Amphitheatre Creek. Elsewhere three rock types are distinguishable within the dominant greywacke and argillite.

(1) *Volcanic rocks*; these crop out on the ridge west of the Avoca River south-west from the farthest upstream hut (Avoca Hut); in Amphitheatre Creek, striking north-west on the north side of Bruce Fault and striking east and dipping 15° south on the south side; and south of Porter Creek, striking west-north-west. They were examined only in Amphitheatre Creek, where they consist of red and green

siliceous bands, with abundant quartz in veins and lenses. Much of the interbedded sandstone and mudstone is green and, less commonly, red, due to tuffaceous material. The beds total a hundred feet.

(2) *Greywacke*: this contains angular chips of argillite up to two inches; chips occur at widely spaced localities and are due to contemporaneous erosion.

(3) *Gabbroic rock*: this was found as boulders in Centre Creek about two miles up from the Avoca River, but was not located *in situ*. Mr J. J. Reed reported as follows:

"The rock is an altered coarse-grained igneous rock with gabbroic texture. The main constituents are plagioclase and pyroxene. Some of the plagioclase crystals exceed 3 mm in length and are cloudy and saussuritized (fine epidote, pumpellyite, carbonate, and sericite) and precise identification is difficult. The pyroxene is a pink-coloured partly altered titaniferous augite in prisms measuring 1·5 mm in length. An accessory constituent is titaniferous iron-ore, largely altered to leucoxene. Chlorite is an abundant secondary mineral. The rock is a saussuritized gabbro."

Induration

Between the Harper and Bruce faults the degree of induration appears to increase slightly northwards. In the sandstones, quartz-veins increase slightly in number in this direction, but jointing remains fairly constant. No systematic variation was observed in the mudstones, which generally contain calcite veins throughout, especially near fault zones; only the coarser, silty mudstones contain rare quartz veins.

In the Avoca River north of Amphitheatre Creek, several thousand feet of mudstone and fine sandstone show corrugations on the bedding surface, the corrugations evidently being incipient slaty cleavage. Mr J. J. Reed reports: "The mudstone possesses a marked fissility due to accentuation of the original shaly bedding. In thin section an incipient slaty cleavage is seen to intersect the bedding at about 45°. The mudstone has suffered incipient recrystallization, but the associated sandstone greywacke would probably not be of higher grade than Chl. 1."

Paleontology and Age

No fossils were found, but, judged by comparison with dated rocks in the central Southern Alps, the rocks are probably Triassic in age.

Structure

The geological map (Fig. 1) illustrates a general strike of about 80°, with steep dips predominating. The few lower dips are near the major

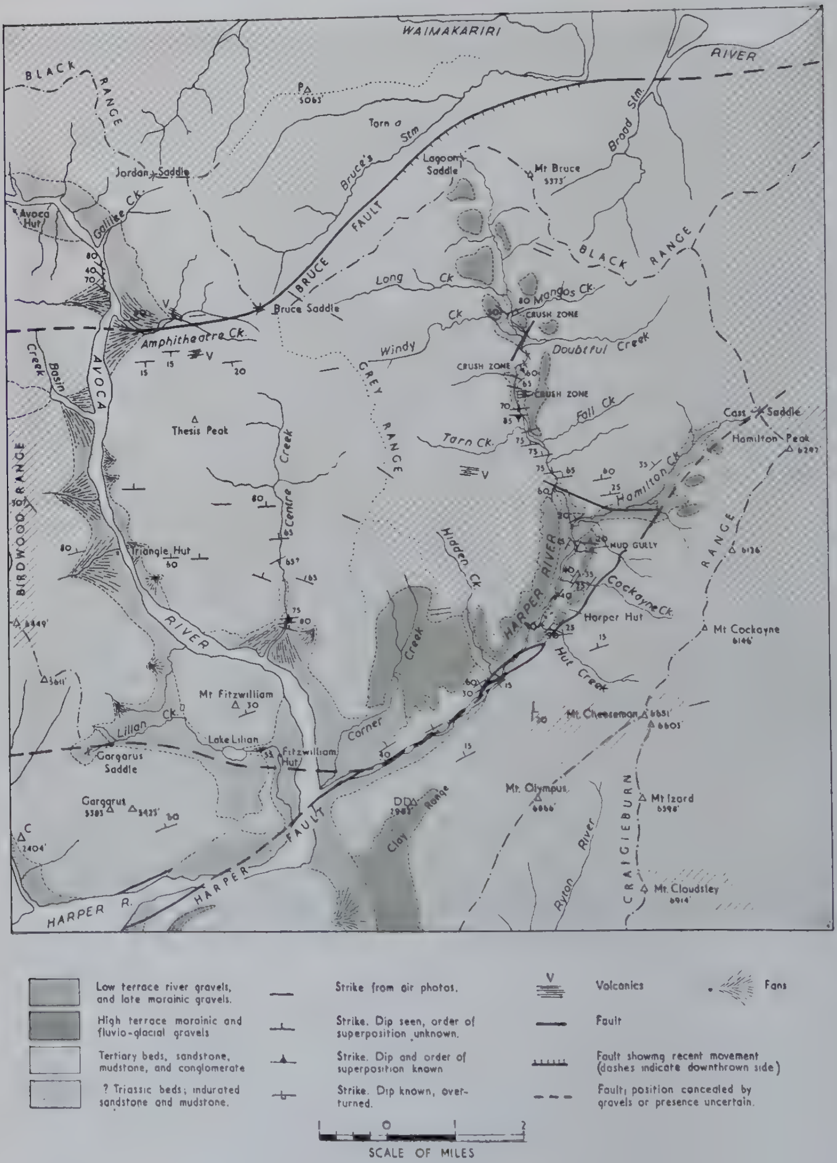

FIG. 1.—Geological map of Harper and Avoca River valleys.

faults. Poorly defined graded bedding at one locality in Centre Creek and two localities in Harper River above the Hamilton Creek junction indicates that the beds become younger towards the south.

The present-day basement structure is believed to be due in part to accentuation of post-Hokonui folding (early Cretaceous) during the Kaikoura Orogeny (mid-Pleistocene).

TERTIARY ROCKS

The stratigraphy and structure of the Tertiary beds are complex, and no section clearly exposes the whole sequence. Arnold, Landon and Pareora age determinations (see below) have been given to fossils from various parts of the sequence; younger Tertiary beds overlie, and possibly some of the basal beds are older than Arnold. Figure 2 shows the details of Tertiary stratigraphy in the Harper Valley upstream from the Avoca River.

Distribution

Apart from a patch of south-east-dipping late-Tertiary gravels in Lilian Creek, the Tertiary beds are confined to the Harper Valley. The beds crop out in discontinuous strips on both banks, bounded by the Harper Fault to the south-east and by an inferred subsidiary fault to the north-west. The outcrops farthest west seen by the writers are three miles below the junction with the Avoca River, but Speight (1917, p. 360) has recorded Tertiary rocks west of the Wilberforce River, on Mount Algidus Station, a few miles farther south-west. From one to two miles above the Harper-Avoca junction, north-east striking beds are exposed almost continuously on the north-west bank. From three miles above the Harper-Avoca junction to the Harper-Hamilton Creek junction, the main outcrops are fairly continuous on the south bank, with fairly well exposed sequences in south bank tributaries; only isolated patches occur on the north bank. Tertiary beds are exposed for a few chains on the north bank of Hamilton Creek just above its junction with Harper River. Throughout the valley the Tertiary sequence is in many places obscured by high-level and low-level gravels.

Content

The best partial sequences are exposed in and near Pinnacle Gully, one and a half miles upstream from the Harper-Avoca junction; in Hut Creek; in the Harper River near the Hamilton Creek Junction; and one mile downstream from the junction, including the south-bank tributaries, Cockayne Creek, and Mud Gully.

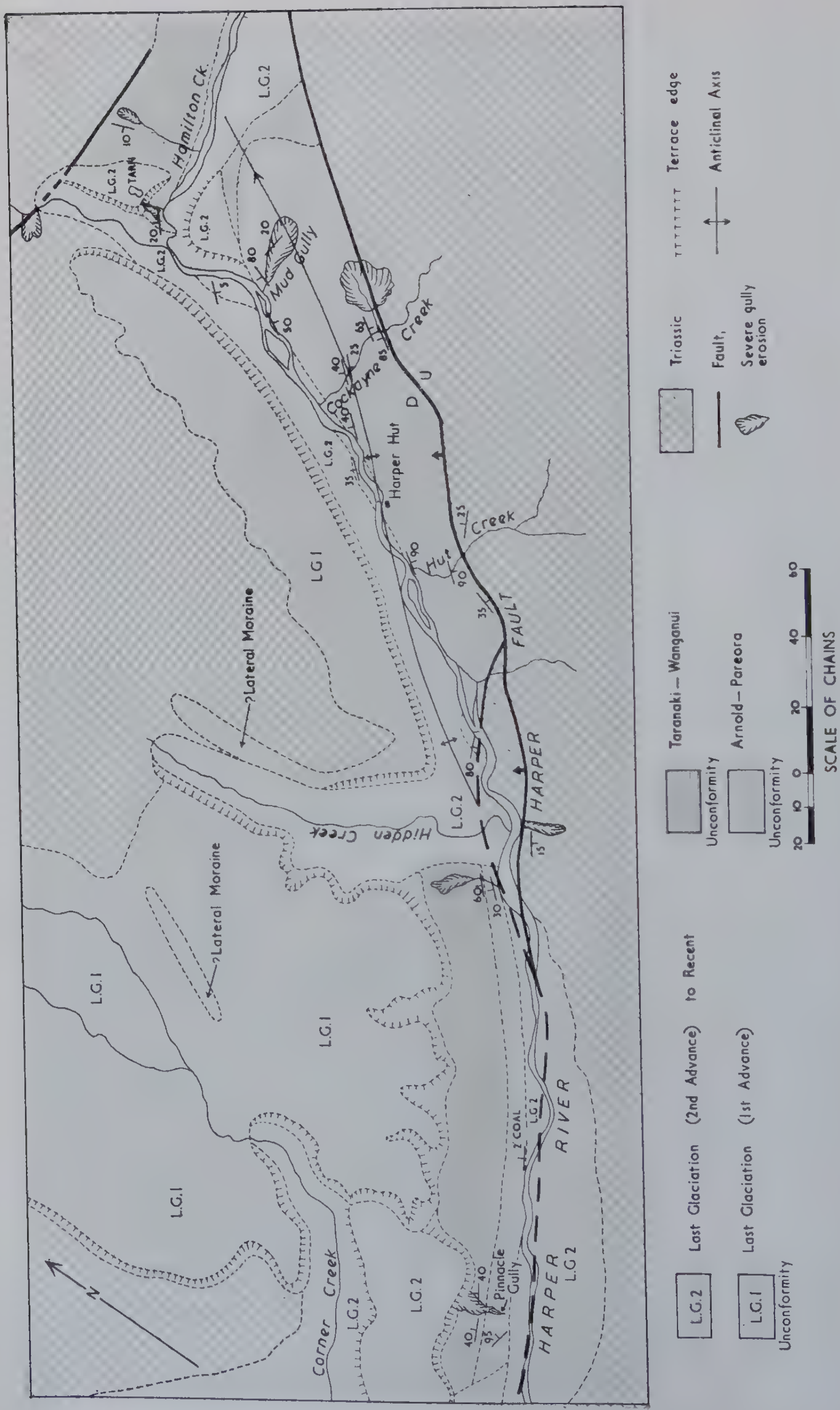

FIG. 2.—The geology of the middle Harper Valley.

Pinnacle Gully Area

Thickness (ft)	*Lithology*	*N.Z. Fossil No. and Age*
Top not seen 60	Greenish-grey gravels with subrounded pebbles in sandy silt matrix. Some bands of silt. Weathers in pinnacles.	
	Inferred Unconformity	
100	Grey-green fine sandstone with cemented bands and shell beds.	S66/520 Waitakian S66/519 Duntroonian
20	White quartz sands.	
30	Grey-green glauconitic fine sandstone with spherical concretions up to 3 ft diam. Concretions with calcite veins, shells, and worm-casts.	S66/518 Bortonian
15	White quartz freshwater sands. Very irregular contact with underlying sands.	
20	Brown and purplish-stained dirty-white freshwater sands. 6 in. of flaky siltstone at lower contact, which appears conformable.	
20 base not seen	Almost black green-grey soft sands.	

Hut Creek

The order of superposition of the following sequence is not certain, but is judged by the apparent position of an anticlinal axis exposed to the north in Cockayne Creek and mapped as passing close to the mouth of Hut Creek.

Thickness (ft)	*Lithology*	*N.Z. Fossil No. and Age*
	Fault-shattered basement rock (Harper Fault).	
Top not seen *c* 60	Green sandstone with irregular cemented bands. Graditional conformable lower contact.	
40	Dirty-white quartz sand.	
30	Greenish glauconitic fine sandstone with cemented bands.	
30	Dirty purplish carbonaceous mudstone with yellow efflorescence.	
c 500	Grey-green fine sandstone with cemented bands. Shell-beds at top. Base not seen (Harper River).	S66/549 Landon-Southland

Cockayne Creek and Mud Gully

From Cockayne Creek to half a mile up Hamilton Creek, no continuous sequence is exposed. The lowest beds crop out on both sides of the axis of a north-east striking anticline in Cockayne Creek, and comprise the following beds:

Thickness (ft)	*Lithology*	*N.Z. Fossil No. and Age*
40	Dirty-white quartz sands.	
500	Grey-green fine sandstone with cemented bands.	
base not seen	Shell-beds near top.	S66/526 Landon-Pareora

Half a mile north-east from Cockayne Creek, the anticline, plunging to the north, is again exposed in Mud Gully, beds on the north-western side of the axis evidently being higher in the sequence than those exposed in Cockayne Creek. The section is:

Thickness (ft)	*Lithology*	*N.Z. Fossil No. and Age*
c 50	Soft green sands.	
100	Blue-grey silts and fine sands with concretionary shell bands.	From boulders:— S66/527 } Hutchinsonian- S66/532 } Awamoan
150	Blue-grey medium sandstone with brown-weathered clay lenses.	
100	Brown and yellow-brown medium sandstone.	
50+	Grey medium sandstone with carbonaceous flecks.	

Hamilton Creek Junction

Thickness (ft)	*Lithology*
c 500	Well consolidated brown gravels.
?	Cemented oyster conglomerate, (not seen in place).
30	Brown muddy silts.

Only 60 ft of the brown gravels were seen at the river, but since similar gravels are exposed in a slip high above the river 20 chains to the north-east the thickness is estimated as at least 500 ft.

Sequence and Age

The stratigraphic column (Fig. 3) illustrates the full sequence, inferred from partial sequences already described and from scattered outcrops along the river bank.

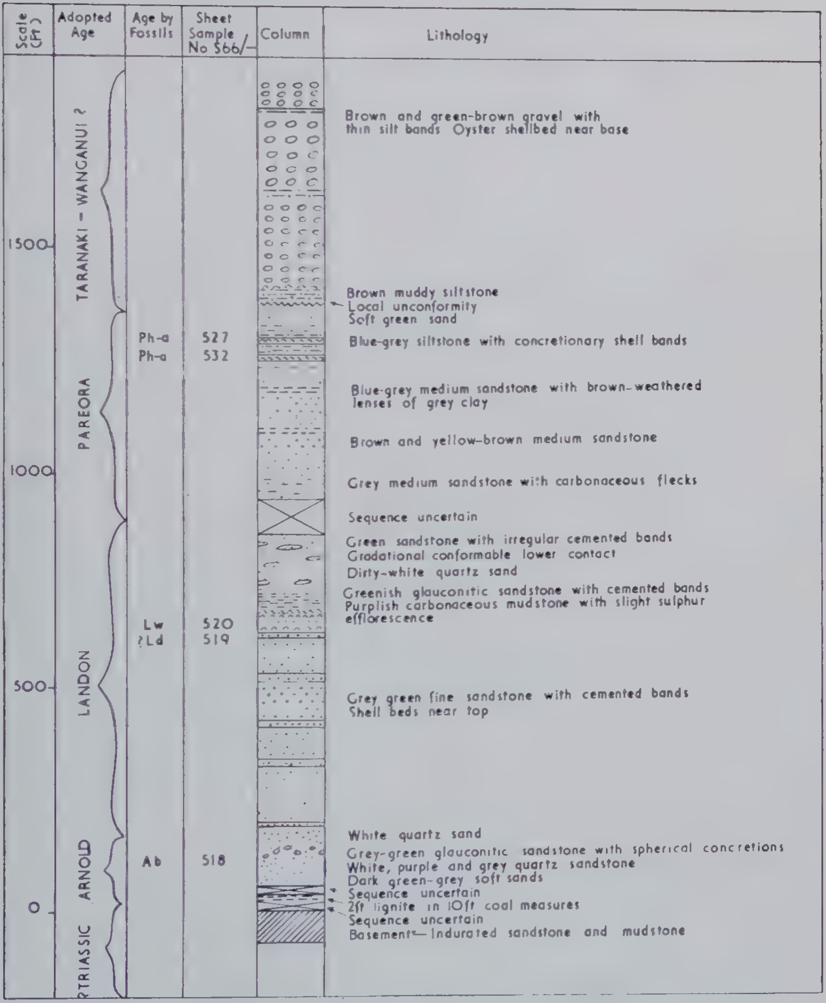
Scale (Ft)
Adopted Age
Age by Fossils
Sheet Sample No S66/—
Column
Lithology
1500
1000
500
0
TARANAKI - WANGANUI ?
PAREORA
LANDON
ARNOLD
?TRIASSIC
Ph-a
Ph-a
Lw
?Ld
Ab
527
532
520
519
518
Brown and green-brown gravel with thin silt bands Oyster shellbed near base
Brown muddy siltstone
Local unconformity
Soft green sand
Blue-grey siltstone with concretionary shell bands
Blue-grey medium sandstone with brown-weathered lenses of grey clay
Brown and yellow-brown medium sandstone
Grey medium sandstone with carbonaceous flecks
Sequence uncertain
Green sandstone with irregular cemented bands
Gradational conformable lower contact
Dirty-white quartz sand
Greenish glauconitic sandstone with cemented bands
Purplish carbonaceous mudstone with slight sulphur efflorescence
Grey green fine sandstone with cemented bands
Shell beds near top
White quartz sand
Grey-green glauconitic sandstone with spherical concretions
White, purple and grey quartz sandstone
Dark green-grey soft sands
Sequence uncertain
2ft lignite in 10ft coal measures
Sequence uncertain
Basement— Indurated sandstone and mudstone

FIG. 3.—Composite stratigraphic column of Tertiary beds.

Arnold Series (Mid.-Upper Eocene)

Dr H. W. Wellman and Dr M. Gage collected the following macrofossils (S66/518; GS 4683) from a concretion in grey, green, and glauconitic fine sandstone near Pinnacle Gully.

Venericardia sp.
Hedecardium sp.
Taras aff. *zealandica*
Tellina sp.
Zeacolpus sp.
Spirocolpus cf. *rudis* (Marshall)
Monalaria concinna (Suter)

According to Dr C. A. Fleming, the fossils are Bortonian in age.

The writers collected numerous specimens of one species of fossil from a concretionary band in coarsely glauconitic sandstone exposed on the north bank of the Harper about 10 chains below the junction of Hamilton Creek. The specimens are poorly preserved, and the tentative Kaiatan age assigned by Dr Fleming depends entirely on the generic determination of the fossil (GS 6344), which he considers to be *Nuculana* (*Pseudoportlandia*) cf. *tahuia* Marwick.

In the Trelissick Basin, 15 miles to the east, coal measures form the base of the late Cretaceous and Tertiary sequence, and it would be expected to find them in a similar position in the Harper River sequence. However, so poor are the exposures that the coal measures shown at the base of the column (Fig. 4) were not found unmistakably in that position. Beds probably of freshwater origin near the base of the section at Pinnacle Gully are Bortonian or a little older. The stratigraphic position of an outcrop of coal and carbonaceous mudstone in the north bank of Harper River 25 chains upstream from Pinnacle Gully is uncertain, but it is thought to belong to the lower part of the sequence, being thus sub-Bortonian. The following proximate analysis (on air-dried coal) of a sample from a 2-ft seam was made by Mr J. M. Hope, Mines Department, Granity:

Moisture	Volatiles	Fixed Carbon	Ash	Sulphur	B.Th.U./lb.
12·1	39·7	42·8	5·4	1·0	10,360

Landon Series (*Lower Oligocene*)

White quartz sands that overlie the sandstone containing spherical concretions in Pinnacle Gully are taken as the basal bed of the Landon Series. The series includes the grey-green sandstones with cemented bands and shell beds that crop out in Pinnacle Gully and Hut Creek, and the interbedded greensand and freshwater beds that overlie the green sandstone in Hut Creek. Dr H. W. Wellman and Dr M. Gage collected *Chlamys* cf. *williamsoni* (S66/519; GS 4684)—possibly of Duntroonian age—from the lower part of the green sandstone near Pinnacle Gully. Shell beds in the upper part, consisting predominantly of mussels, yielded the following (S66/520):

Athlopecten athleta (Zitt.)
Modiolus n. sp.
Brachydontes aff. *huttoni* (Suter)
Divaricella sp.
Ostrea sinuata Lam.
?Eucominia sp.
Bryozoan

These indicate a Waitakian age.

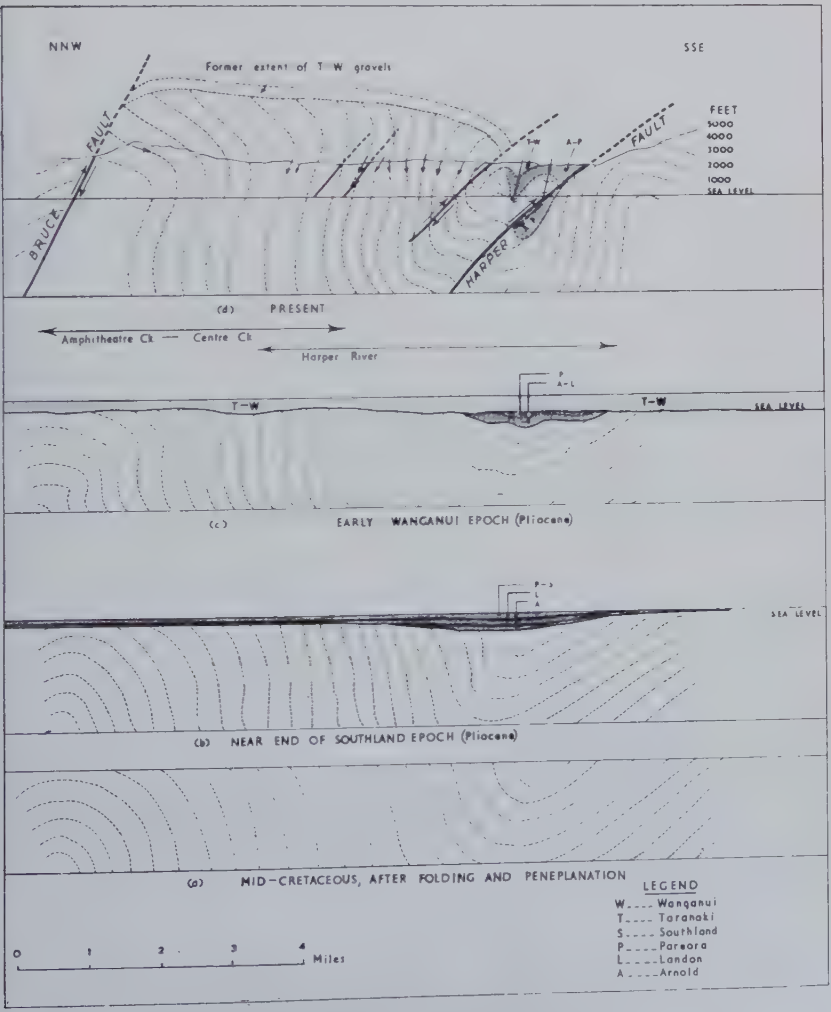

Fig. 4.—Development of structure.

Pareora Series (Upper Oligocene)

All the beds in Mud Gully are placed in the Pareora Series. Collection S66/527, made by Dr H. W. Wellman and Dr M. Gage from a boulder at the base of a large slip in the gully, yielded the following (GS 4999):

Pteromyrtea sp.
Chione n. sp. aff. *stutchburyi* (Gray)
Eumarcia n. sp.
Batillona cf. *hectori* (Harris)
Taxonia n. sp.
Struthiolaria subspinosa Marw.
Maoricrypta radiata (Hutt.)
Polinella n. sp.
Polinices cf. *huttoni* Iher.
Cominella (*Acominia*) aff. *errata* (Fin.)
Mauira cf. *huttoni* (Sut.)
Baryspira (*Alocospira*) *hebera* (Hutt.)
Pupa n. sp.

A boulder (S66/532; GS 5121) at the mouth of the gully contained:

Angulsu aff. *edgari* Ired.
Maorimactra sp.
Struthiolaria tuberculata (Hutt.)
Sigapatella sp.
Maoricrypta sp.

Both collections are Hutchinsonian-Awamoan in age.

Taranaki-Wanganui Series (Upper Miocene-Pliocene)

The Pareora beds are overlain by thick deposits consisting principally of gravel. The actual contact was not observed, but a 40° unconformity is probable in Pinnacle Gully, and a 30° unconformity in the small gully 20 chains downstream from Hidden Creek. No fossil evidence of age is available and these gravels are tentatively placed in the Taranaki and Wanganui Series; the preserved thickness may exceed 1,000 ft. They crop out at widely separated localities, resting on Pareora deposits near the junction of Hamilton Creek, and on progressively older deposits towards the south-west. Four chains up Hamilton Creek on the north bank, the deposits consist of gravels striking north-east and dipping 30° north-west, overlying muddy silts. Other exposures occur in a small north-bank tributary about 20 chains downstream from Hidden Creek, dipping north-west; in Pinnacle Creek, dipping 40° north-west and showing bad-land erosion; and on the south side of Lilian Creek, dipping 55° south-east. The lower beds above the unconformity are grey and unweathered, whereas the higher beds are rusty-brown, similar to the youngest folded gravels in much of the South Island.

Structure of Tertiary Beds

The structure of the other Tertiary beds is complex, dips both to north-west and south-east being generally high; the strike is generally north-east. Several tight folds are inferred, but only one anticline which strikes north-east has been recognized with certainty, and other folds are postulated only to explain the distribution and recorded dips of Tertiary beds. The axis of the anticline plunges north-east from Cockayne Creek to Mud Gully, being clearly exposed in both places; south of Cockayne Creek it passes below the mouth of Hut Creek and extends to Hidden Creek. Judged by dips and stratigraphy near the junction of Hamilton Creek, a synclinal axis lies 10 chains north-west of, and parallel to, the main anticlinal axis in that area.

The tilted gravels belonging to the younger Tertiary beds of Taranaki-Wanganui age dip consistently north-west along the Harper River, but the south-east dip in Lilian Creek may be representative of the dip along the north-west contact of the gravels with basement, elsewhere obscured by late Pleistocene morainic gravels. This contact is, however, probably faulted.

Harper Fault is considered to dip north-west at a moderate angle, as it lies farther to the south-east on ridges than in creeks. The inferred north-west dip is supported by an overturned north-west dip of 85° in Tertiary beds close to the fault in Cockayne Creek.

Recent movement on Bruce Fault, north-west of Lagoon Saddle, has been recorded by Speight (1938, p. 706) and Wellman (1953, p. 287), the north-west side being upthrown; the dip is to the north-west (Wellman, *op. cit.*), Bruce Fault thus being a reverse fault. Harper Fault, by analogy with Bruce Fault, is probably also a reverse fault.

DEVELOPMENT OF STRUCTURE

The important features leading to an interpretation of Mesozoic and Tertiary structures are:

(1) The Triassic rocks become younger southwards; the northward dips, although some are at only moderate angles, indicate overturning.

(2) The degree of overturning increases towards the Tertiary beds.

(3) The tight folding of the Tertiary is due to compressive folding.

(4) Harper Fault is closely associated with the narrow strip of Tertiary beds, and hence will also be due to compressive folding. This would be consistent with it being a reverse fault despite the presence of Tertiary beds on the north-west, apparently upthrown, side of the north-west dipping fault.

(5) The general parallelism of early Tertiary and late Tertiary rocks, separated by an unconformity, shows that late-Tertiary fold-

ing took place along lines parallel to those of mid-Tertiary folding.

(6) The mid-Tertiary unconformity, varying in time value and angular discordance along the narrow Tertiary belt, shows that this belt was markedly unstable long before the main pulse of the Kaikoura Orogeny.

These considerations form the background to the tentative interpretation of development of structure shown in Fig. 4. The interpretation shows:

(1) Folding to be dominant in the deformation of the Tertiary beds.

(2) The Harper Fault to be a late fracture through beds already strongly folded—this explains why the beds are preserved on the upthrown side of a reverse fault, instead of being removed by erosion as might be expected if the fault had been active throughout the Tertiary.

(3) Continuity of slow deformation along the same general trends from the post-Hokonui Orogeny through the Tertiary to the Kaikoura Orogeny, so that Tertiary folding is superimposed on a simple pattern of post-Hokonui folds. The low-angle overturning of basement rock close to the Tertiary beds is explained as due to the effect of continuous slow folding.

QUATERNARY

The Harper and Avoca valleys above their junction show contrasting physiographic forms. The Avoca Valley is flat-bottomed, with a U-shape modified by recent fans; the Harper Valley has a narrow flood-plain up to the Hamilton Creek junction; above the junction both branches flow mostly through gorges.

In addition to the contrast at low levels in the two valleys, a prominent high-level terrace which is characteristic of the Harper is absent in the Avoca (Fig. 1). The terrace averages about 500 ft above the Harper River up to Hamilton Creek, above which the river and terrace gradually converge.

The high-level terrace is marked by tarns in hummocky morainic topography called the Clay Range, on the western slopes of Mt Olympus; southwards a prominent valley, immediately south of the mapped area, and Ryton River, south-flowing from Lake Catherine, continues the valley to Lake Coleridge. This valley is flanked to the east by the moraine of the high-level surface. Ice clearly came down the Harper Valley, some pushing southwards from the Harper-Avoca junction, and the rest continuing south-west to join the Wilberforce ice. The greater part of the Harper ice came from the Waimakariri Valley across Lagoon Saddle, where the ice-smoothed surface clearly shows on air photographs. Distributary ice from the Waimakariri Valley appears also to have moved across Cass Saddle into Hamilton Creek. Judged by the valley profile and the thickness of the morainic gravels—about 50 ft—the valley floor at that time was several hundred feet above the present valley-floor. Air photographs show marked ridges, resembling lateral moraines, on the east sides of Hidden and Corner creeks, descending to join the high-level terrace; the south-facing shady slopes of the southern end of the Grey Range appear to have fed minor glaciers.

The high-level surface does not show in the Avoca Valley because a more recent ice advance, described below, has cut a deeper valley wide enough to destroy all traces of the earlier ice-floor. During the later advance, Waimakariri ice did not come over Lagoon and Cass saddles into the Harper Valley.

After retreat of the ice of the first advance, the rivers cut down in gorges below the high-level valley floors, easing the way for low-level erosion by later ice in the Avoca Valley. During the second advance, ice from the Avoca Valley extended past the Harper-Avoca junction at least as far south as Lake Catherine, which is dammed by moraine. One lobe of the Avoca glacier flowed to the west of Mt Fitzwilliam, leaving on retreat the depression containing Lake Lilian. Moraine on each side of the Avoca River half a mile below Triangle Hut was probably deposited during a pause or minor re-advance during retreat.

In Hamilton Creek, immediately upstream from the junction with Harper River, ill-sorted angular greywacke fragments, set in a silty sand matrix containing lumps of wood, show at river level below the rounded gravels of a low terrace: the deposit resembles moraine, but is interbedded with soft puggy clay not typical of glacial beds. A few chains upstream, more wood fragments were found at the base of a grey clay that overlies late Tertiary gravels. The wood fragments, N.Z. ^{14}C No. 72 and No. 73 (Fergusson and Rafter, 1957, p. 748) gave ^{14}C ages 4620 ± 80 and 4550 ± 80 years respectively, and are thus too young to be from deposits of a glacial advance, as they were at first thought to be. The presence of undoubted slumped beds at the junction of the branches makes it certain that the beds containing the wood are also slump deposits, probably in part slumped high-level moraine. The wood dates a major slump probably due to an earthquake associated with movement at one of the major faults of the district. The recent fault scarp of the Bruce Fault (Speight, 1938; Wellman, 1953) must be post-glacial in age, and the slump in the Harper River may possibly indicate its age.

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GRANITES AND MINERALIZATION IN NEW ZEALAND*

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Summary

Granite in New Zealand is confined to the South Island and Stewart Island. There are three major meridionally trending belts in north-west Nelson—Separation Point to Mt Murchison, Kahurangi Point to Ahaura River, and Paparoa Range to Kongahu Point. Isolated granite masses are known in Westland and extensive areas in Fiordland and Stewart Island. The Separation Point to Mt Murchison granite differs from the others in being essentially a soda-alkali type.

Directly related to granite are copper-molybdenum-gold-silver-lead-zinc lodes at Mt Radiant and tungsten-tin lodes at Port Pegasus, Stewart Island; probably related are the Reefton gold lodes, many minor auriferous lodes, and a barite-fluorite deposit; possibly related are the gold-scheelite lodes in the Otago and Marlborough schists. Mining has ceased except for scheelite which is worked by small parties at Glenorchy.

Present knowledge of the age of the granites and mineralization is summarized in a table.

INTRODUCTION

Discussion of granites and related mineralization in New Zealand is handicapped by lack of detailed knowledge of the granite areas and by the virtual cessation of mining so that in many cases reliance must be placed on old reports for descriptions of the mineral deposits.

Granites† are confined to the South Island and Stewart Island (Fig. 1). Extensive exposures, covering more than 2,000 sq. miles, form the bulk of the highlands in north-west Nelson where there are three major meridionally trending belts—Separation Point to Mt Murchison, Kahurangi Point to Ahaura River, and Paparoa Range to Kongahu Point. Further south in Westland granite mountains and hills crop out intermittently along the coast to the west of the Southern Alps. Still further south, and separated from the Nelson and Westland granites by the Alpine Fault, a major structural feature in the South Island, are large granite masses in Fiordland and Stewart Island.

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*Paper originally prepared for the Sydney (1955) meeting of the Australian and New Zealand Association for the Advancement of Science.

†Granite is used in two senses, (a) as a collective term covering all rocks in a granitic terrain, and (b) as a strict petrographic term. The sense used will be clear from the text.

N.Z. J. Geol. Geophys. 1: 47-64.

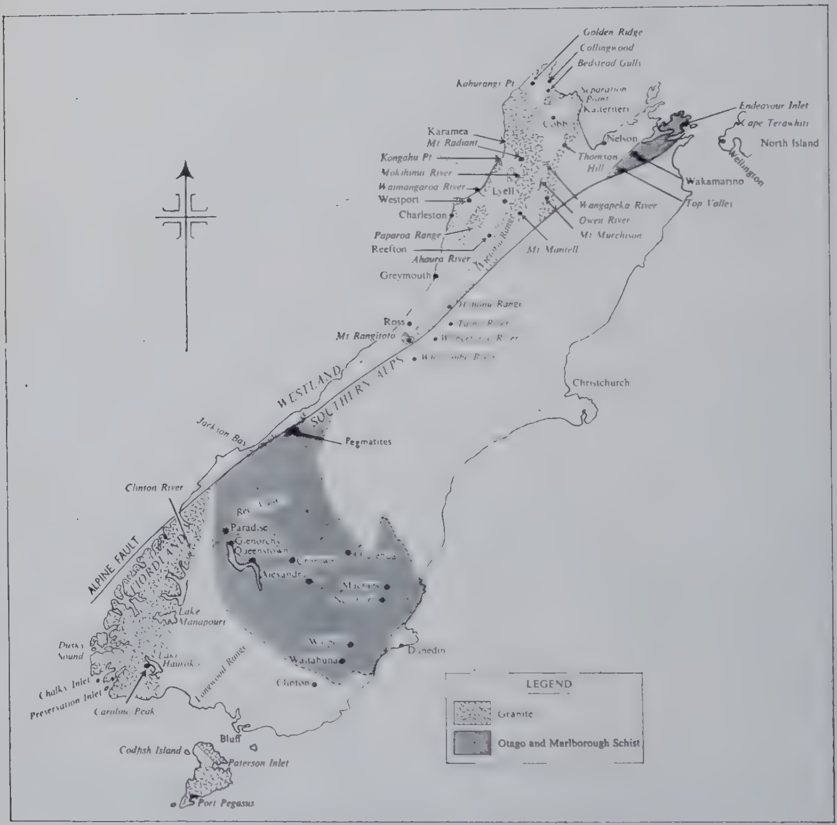

FIG. 1.—Locality map showing distribution of granite rocks in New Zealand.

OCCURRENCE AND DESCRIPTION OF GRANITE AREAS

No systematic detailed examination of the granite areas has yet been made so that only meagre qualitative, quantitative, and chemical data are available. The following account is based on published reports, and on investigations by the author.

Separation Point to Mt Murchison

The main mass of the eastern granitic belt in north-west Nelson extends from Separation Point to Mt Murchison (Fig. 1), a distance of over 70 miles; it is emplaced in the northern and central parts in the fossiliferous argillites, phyllites, quartzites, schists, and gneisses of the upper Ordovician Mt Arthur Group, and in the south-east probably in basic lavas and tuffs of the Permain Brook Street Volcanics (Wellman, 1952). Typically the granite is a massive, white, leucocratic soda-alkali granite* consisting essentially of quartz, alkali feldspar in which sodic plagioclase (albite to acid oligoclase) exceeds potash feldspar, and minor biotite. In places porphyritic alkali types with large orthoclase crystals are developed and have ceramic possibilities (Henderson, 1950). Orbicular varieties are known from the Kaiteriteri region. Hornblende is the main ferromagnesian mineral in some areas and its presence marks the transition into more basic types (syenites, amphibolites, norites, gabbros) that are developed at the rock contacts, particularly with the marble in the north and the basic lavas in the south. In the production of basic rocks at contacts with marbles and volcanics the granite batholith can be compared with the classic Haliburton-Bancroft area in Canada.

Kahurangi Point to Ahaura River

The central granitic belt, the largest in north-west Nelson, extends from Kahurangi Point to Ahaura River, a distance of 120 miles and averages about 12 miles across (Fig. 1). It is emplaced on its western margin within the unfossiliferous greywackes, argillites, fine conglomerates, phyllites and schists of the probably Precambrian Waiuta Group (Suggate, 1957), and on the eastern margin in the fossiliferous carbonaceous argillites, greywackes, quartzose greywackes, phyllites and schists of the lower Ordovician Aorere Group. At the contacts hornfels or spotted schists are developed or else there are "lit-par-lit" injections of granite into altered sedimentary rocks. The granite is porphyritic, or massive, occasionally gneissic, and has orbicular texture well developed in boulders from the Karamea district (Marshall, 1939). The types range from pink, generally porphyritic, alkali granites to the more common white to grey biotite calc-alkali granite, adamellite or granodiorite. Dioritic rocks also occur.

Paparoa Range to Kongahu Point

The western granitic belt in north-west Nelson forms the coastal ranges between Greymouth and Westport and extends north in isolated patches to Kongahu Point (Fig. 1). It is emplaced within the unfossiliferous greywackes and argillites of the probably Precambrian Greenland Group which lithologically resemble those of the Waiuta Group but differ in possessing a regular north-west strike in contrast to the north-east strike of the Waiuta Group. The granitic rocks can be divided into a granite formation and a gneiss formation whose age relationship is still in doubt. Unlike the granite, the gneiss is nowhere seen in contact with the sedimentary rocks but is commonly so intermingled with the granite that separate mapping is virtually impossible although the gneisses are generally readily distinguished from the gneissose granites. The gneisses show distinct, thin ($\frac{1}{16}$-$\frac{3}{8}$ in.), commonly contorted bands of alternating leucocratic and melanocratic minerals. In places bands 20 ft thick consist almost entirely of biotite.

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*Except for the term "soda-alkali", the volcanic and plutonic classification used in the paper is that of Nockolds (1954). Soda-alkali appears most appropriate to describe an albite-oligoclase granite rather than include the rock in the adamellite class.

The granites are massive, porphyritic, or gneissic, with biotite the main ferromagnesian mineral, although hornblende also occurs. The main types appear to be alkali and calc-alkali granites which pass into granodiorites or diorites in places. A noteworthy feature is the association of quartz porphyries with the granitic rocks; these are commonly marginal facies to the granitic rocks and are remarkable for the persistent occurrence of small angular inclusions of hornfels, which vary in size from microscopic fragments to xenoliths an inch or more in diameter and which may be sufficient to give the rock the appearance of a breccia (Morgan and Bartrum, 1915, p. 101). The most characteristic alteration of the country rock at the granite contacts is to hornfels; in places the hornfels becomes almost indistinguishable from the granite (Morgan and Bartrum, 1915, p. 70).

Westland

Granitic rocks outcrop intermittently along the coast to the west of the Southern Alps. They have intruded the unfossiliferous greywackes and argillites which are altered to hornfels at the granite contacts. The most westerly outcrops, extending in isolated masses from Jackson Bay to Mt Rangitoto, are emplaced within the north-westerly striking Greenland Group and may represent the southerly extensions of the Paparoa Range to Kongahu Point granite. The more easterly exposures of the Hohonu Range probably intrude the north-easterly striking Waiuta Group and can be regarded as extensions of the Kahurangi Point to Ahaura River granite.

Fiordland

In Fiordland, granites are known particularly from the region of Preservation and Chalky inlets (Benson, 1934; Benson and Bartrum, 1935) and further north around Lake Manapouri (Turner, 1937-8). Recent mapping by members of the New Zealand Geological Survey has greatly extended knowledge of granitic rocks in the area between. Near Preservation and Chalky inlets, pink porphyritic or massive alkali and calc-alkali granites intrude a fossiliferous lower Ordovician group of black and grey argillites, greywackes and quartzites. Other granitic rocks, largely gneissic tonalites, are emplaced in "lit-par-lit" manner in schists and hornfels that are metamorphosed equivalents of the lower Ordovician rocks, and also in an unfossiliferous highly metamorphic Precambrian or lower Paleozoic group of calc-silicate hornfels schist, feldspathic quartzites and schists. Near Lake Manapouri the ancient metamorphic group of dominantly hornblende gneisses are invaded by "synchronous" gneissic tonalites ("trondhjemites"), granodiorites ("oligoclase granites") and adamellites, and by "subsequent" smaller masses of pink alkali granite. The tonalites at Manapouri differ from those at Preservation Inlet in their lower biotite content and more acidic composition of the plagioclase (Turner, 1937-8, p. 246). Recent mapping between Dusky Sound and Lake Hauroko has shown that synchronous and subsequent granitic rocks probably similar to those at Manapouri are emplaced in a metamorphic group of schists and quartzites.

Stewart Island

The southern part of Stewart Island is composed mainly of white, massive or gneissic, biotite calc-alkali granite in which are exposed small roof pendants of micaceous schists, quartzites and calc-silicate hornfels (Williams, 1934); the hornfelses are similar to those found in Fiordland (Benson, 1934, p. 414). The granite is bounded in the north by a narrow belt of low grade metamorphic rocks which extend from Codfish Island in an easterly direction along the southern shoreline of Paterson Inlet. The northern part of the island consists of metamorphosed lavas and tuffs, diorites, amphibolites and granites.

ORIGIN OF THE GRANITES

Definite statements on the origin of the granites are not possible with the available data. It is the writer's belief that no single theory will explain all the occurrences and that granitization, magmatism, metasomatism, reaction and differentiation, basification, and rheomorphism will be applicable concepts.

MINERALIZATION DIRECTLY RELATED TO GRANITE

Copper-molybdenum-gold-silver-lead-zinc lodes

The only noteworthy deposits are in the Mt Radiant area where the metalliferous veins are confined to a zone about $1\frac{1}{4}$ miles wide in the Kahurangi Point to Ahaura River granite (Webb, 1910). Steeply dipping pegmatitic veins range from a few inches to over 20 ft in length and apparently follow master joints in the granite. The veins can seldom be traced far and are probably lenticular in shape, pinching out rapidly in both vertical and horizontal directions. Sometimes well defined walls are present but more commonly one or both may be indefinite; the veins in places are greisen-like or exhibit a mass of reticulating veinlets resembling a stock-work. Quartz is the most abundant gangue material though mica and feldspar also occur. The ores are generally copper minerals, particularly chalcopyrite, usually accompanied by pyrite in greater or lesser amounts, invariably some molybdenite, and usually very small amounts of gold and silver; lead and zinc sulphides may also be present. Chalcopyrite and molybdenite were mined between 1916 and 1917. Webb (1910, p. 25) considered the ores to be deposited largely subsequent to a fissuring of the vein material, and that this was effected either by ascending magmatic solutions, or descending meteoric waters acting on original metalliferous constituents of the ore.

Minor deposits are a lode containing gold-silver-lead-copper-zinc in granite at Isthmus Sound, Fiordland (McKay, 1896, p. 42), a gold and copper lode in granite near Port Pegasus, Stewart Island (Skey and McKay, 1890, p. 420), and a quartz-galena lode in granite of the Victoria Range east of Reefton (H. E. Fyfe, pers. comm.).

Tungsten-tin lodes

In the Port Pegasus district at the southern end of Stewart Island a wolframite-cassiterite lode occurs in biotite schists and quartzites that are roof pendants in granite. Although the deposit has been extensively prospected, particularly between 1912 and 1916, no economic lodes have been located. The most detailed accounts of the deposits are provided by Williams (1933, 1934a and b). "The lode zone, which traverses the dark brown schist, varies from a few feet to a few hundred in width, and consists mainly of a greyish, sugary quartzose rock (greisen) enclosing an anastomosing series of metalliferous veins only a few of which exceed 6 inches in width. The boundary between the greisen and the schist is sharply defined, but lenticular apophyses appear throughout the neighbouring schist, forming eye-shaped distensions in the foliae. Only rarely do the metalliferous veins pass from their greisenous host into the neighbouring schist" (Williams, 1934a, p. 414). The metalliferous veins are made up predominantly of coarse-grained quartz in which topaz and garnet are irregularly scattered. Masses of wolframite are clearly visible in hand specimen and consist of aggregates, the individuals of which rarely show idiomorphic outlines. Cassiterite is much less abundant than the wolframite and occupies cavities in the surface of the wolframite clusters. The metalliferous lodes are considered to be late magmatic residues occupying a fracture system in the greisen.

Probably to be included in this type are quartz-wolframite lodes in the unfossiliferous upper Ordovician Mt Arthur rocks in the Mt Mantell region near the contact with the Kahurangi Point to Ahaura River granite (Morgan, 1927, p. 107; H. E. Fyfe pers. comm.).

Other minerals

Pegmatites throughout New Zealand are poor in minerals; occasionally sheet mica is of sufficient size and quality to warrant mining (Morgan and Bartrum, 1915, p. 124; Wellman, 1947, and rare beryl has been found at Charleston and Paterson Inlet, Stewart Island (Skey and McKay, 1890, pp. 415-8). Economic deposits of radioactive minerals are unlikely to be found in the granites and gneisses according to tests made by Nicholson (1955). Monazite is known to occur in gneisses of the Charleston district and is probably the source of monazite found in the beach sands of the West Coast (Hutton, 1950, p. 699).

Mineralization Probably Related to Granite

Auriferous lodes in rocks intruded by granite

The most important area is the Reefton district, whose quartz lodes are described by Henderson (1917), Downey (1928), and Gage (1948). The quartz veins extend north-north-west for more than 20 miles in the alternating beds of thick massive greywacke and thin weaker argillite, rocks of the probably Precambrian Waiuta group that are altered to spotted schist and hornfels at the granite contacts. The lodes are sub-parallel to, and about three miles west of, the elongated granite mass of the Victoria Range (Kahurangi Point to Ahaura River granite). "The lodes are in well-marked slickensided fissures, traversing a much-fractured zone which numerous dykes of basic rocks, probably from the undifferentiated invading magma, had penetrated before ore deposition. The lodes strike a little east or west of north, and dip steeply, for the most part to the west. The structure of the ore shows that the fissures were active while the lodes were forming. Movement was renewed during the Pliocene, and in consequence many of the ore-bodies are shattered and broken. The ore is not continuous along the ore channels, but forms flat irregular lenses that succeed each other, and in places overlap, down shoots that all pitch north and are generally well defined. Some of the shoots, several of which may occur in one fissure, are undoubtedly, and the rest are probably, structurally controlled. The ore consists of relatively coarse-textured quartz, but numerous shears containing crushed and recemented quartz country and sulphides may impart to it a decidedly banded appearance. In addition to free gold, the common constituents are pyrite, arsenopyrite, and stibnite. Lead and copper are found in small amount in a few lodes. The mines are dry; meteoric waters circulate very feebly, and there is no secondary enrichment. Near the lodes the country is sericitized, but its imperviousness prevented wide alteration. . . . The ore bodies in the Energetic-Wealth of Nations mine maintained their size and tenor through a vertical range of 2,300 ft and though precise data are lacking the evidence suggests a range of original deposition at least twice as great" (Henderson, 1930b, p. 156). The strong but not absolute evidence linking the Reefton quartz lodes with granite has been summarized by Henderson (1917, pp. 121-3).

The mines of the Reefton district were worked between 1871 and 1951, the gold produced being 2,079,917 oz., valued at £9,839,406. The last mine closed, that at Blackwater about 12 miles south of Reefton, was the deepest, with the main shaft 2,612 ft in depth. The age of the lodes cannot be precisely fixed. Both Henderson (1917) and Gage (1948) considered they post-dated the infaulted Devonian rocks of the Reefton district although no lodes occur in these rocks. The granitic rocks with which the lodes are probably related were considered to be upper Jurassic in age by Henderson (1930a, p. 260) whereas Gage (1948, p 32) thought a late Paleozoic age more probable.

Lodes similar in nature and mineral content to those at Reefton are found in the Westport, Paparoa, Ross and Lyell districts (Downey, 1928; Morgan and Bartrum, 1915, Morgan, 1908; 1911) but none of these areas can be compared in yield with the Reefton district. The lodes of the Lyell district may be a continuation of the Reefton lodes, although apparently most of the Lyell claims depended on small but astonishingly rich leaders, none of which could be followed to any depth (Henderson, 1917, p. 127).

Mineralization is known in Ordovician sediments, particularly from areas near Golden Ridge, Bedstead Gully, Wangapeka, Owen, and Preservation Inlet. In the Golden Ridge area the lodes are confined to a belt of lower Ordovician Aorere rocks about 1¼ miles long and a few chains wide; in this narrow belt payable returns were obtained throughout a vertical range of over 450 ft (Bell, Webb, and Clarke, 1907, p. 90). The formation of the lodes was apparently controlled by a narrow band of carbonaceous, graptolite-bearing, slate or argillite, although the lenticular quartz sheets are not confined to any particular position in the argillite band. The quartz contained gold, pyrite, marcasite, minor silver, and a little native copper. Secondary enrichment was considered by Bell, Webb, and Clarke (1907, p. 90) to have taken place to a remarkable extent and to be responsible for the exceedingly rich bonanzas that were occasionally found. The Bedstead Gully field contains the once profitable Johnston's United mine where the auriferous quartz veins occur at or near the contact of black graphitic phyllites with overlying sericitic schists. Mining revealed the presence of three distinct zones . . . an uppermost zone of gossan in places highly auriferous, a middle richly auriferous sulphide zone in which the quartz gangue contained granular pyrite interspersed with bunches of galena, sphalerite and possibly tetrahedrite, and a lowest "lean sulphide" zone containing only pyrite with a very low gold and silver content (Bell, Webb, and Clarke, 1907, p. 90). Near the Owen and Wangapeka rivers segregated quartz veins, containing galena, sphalerite and stibnite, in the upper Ordovician Mt Arthur sediments have yielded a little gold (Downey, 1928).

Barite-fluorite Deposit

There is a small barite-fluorite deposit near Thomson Hill in the Wangapeka district of Nelson (Macpherson, 1944), but the exact relation to the surrounding rocks is not known. The deposit lies near the contact of quartzites, marbles, and phyllites of the upper Ordovician Mt Arthur Group, with amphibolites and diorites that are basic margins to the Separation Point to Mt Murchison granite outcropping less than ½-mile east of the deposit. The barite and fluorite have not been mined.

MINERALIZATION POSSIBLY RELATED TO GRANITE

The most important deposits are the gold-scheelite lodes in the Otago and Marlborough schists, which are low grade metamorphic rocks, of the chlorite zone, derived from progressive regional metamorphism of greywackes and argillites and intercalated lavas, tuffs, and cherts. The schists pass into fossiliferous (Permian) volcanics on one margin and on the other into greywackes and argillites that are unfossiliferous except for sparse upper Triassic fossils.

The lodes generally cut across the schistosity planes and can be divided into:

(i) Lodes in which gold is the profitable constituent—lodes in the Queenstown (Park, 1909), Cromwell (Park, 1908), and Alexandra (Park, 1906) regions, Rees Valley (Willett, 1940), the Oturehua and Nenthorn fields (Williamson, 1939), the majority of the lodes in the Waipori district (Marshall, 1918), and the bulk of the Marlborough lodes (Henderson, 1935a).

(ii) Lodes in which scheelite is the profitable constituent—lodes at Glenorchy and Paradise in Otago (Reed, 1945).

(iii) Lodes in which both gold and scheelite occur in economic amount—lodes near Macraes (Williamson, 1939), certain lodes in the Waipori region (Marshall, 1918), and lodes at Wakamarina and Top Valley in Marlborough (Henderson, 1935a; Downey, 1928).

The gangue material is always quartz which is usually accompanied by pyrite, and by arsenopyrite in the Otago lodes. Appreciable amounts of stibnite are present in the lodes at Endeavour Inlet in Marlborough (Henderson, 1935a, p. 21), Alexandra (Park, 1906, p. 36) and near Waipori (Marshall, 1918, p. 43) in Otago. Wolframite was found in a lode in the Waipori district (Marshall, 1918, p. 40). Copper lodes are known from Waitahuna (Marshall, 1918, p. 44) and Moke Creek near Queenstown (Hutton, 1934) but it is not known whether they have a similar origin to the quartz lodes.

The origin of the quartz lodes is still debated. The three theories proposed are: lateral secretion from the country rock (Marshall, 1918; Morgan, 1920); secondary enrichment of lean primary ores (Henderson, 1935b); magmatic derivation from a subjacent but unexposed granite batholith (Finlayson, 1908; Williamson, 1939; Reed, 1945). Gold mining has ceased but small parties work the scheelite deposits at Glenorchy.

Other deposits included in this section are the poorly auriferous quartz lodes found in the greywackes and argillites, some at least of upper Triassic age, that grade into the Otago, Westland, and Marlborough schists. These lodes are known particularly from the Wilberforce, Taipo, and Whitcombe areas in Westland (Bell and Fraser, 1906, p. 51; Morgan, 1908, p. 143; Downey, 1928, pp. 22-8) and from the Terawhiti region in the Wellington Province of the North Island (Park, 1888). Probably these lodes originated in a similar manner to those in the Otago and Marlborough schists. If they are related to granite, then the batholith must be post-Triassic in age.

Mineralized bands in the probably Precambrian schists and quartzites of the Dusky Sound district have been described by Park (1924); these bands, whose origin is uncertain, consist mainly of pyrite, pyrrhotite, and a little chalcopyrite. Similar bands are known in the Caroline Peak area in Fiordland. Poorly auriferous quartz lodes occur in the low grade schists exposed on the southern shores of Paterson Inlet, Stewart Island (Skey and McKay, 1890, p. 419). Granitic rocks are probably the source of cassiterite and scheelite found in many gravels on the West Coast (Morgan, 1927, pp. 21, 90). Possibly the carbon dioxide solutions giving rise to the talc-magnesite and quartz-magnesite deposits in the Cobb district of Nelson (Wellman, 1943) originated from granite.

AGE AND CORRELATION OF THE GRANITES

None of the granites can be precisely dated. A common belief is to regard the granites as being emplaced in one period, which has been considered to be late Paleozoic (Macpherson, 1946), or alternatively late Mesozoic and coeval with the "post Hokonui orogeny" responsible for the folding of the older rocks (Henderson, 1930b, p. 155). An upper limit to the age of the granites is provided by the abundance of pebbles in Miocene conglomerates.

The evidence bearing on the age of the granites can be summarized under the following headings:—

Distribution and Age of Rocks Containing Granitic Debris

The extensive, generally unfossiliferous, greywackes and argillites of the probably Precambrian Greenland and Waiuta groups, and of the upper Paleozoic and lower Mesozoic "Alpine Facies" of Wellman (1952) are derived essentially from granitic terrains (Reed, 1957). In Ordovician and Devonian rocks meagre petrographic data point to the greywackes and argillites being derived from granite (Bell, Webb, and Clarke, 1907, p. 44; Benson and Bartrum, 1935, p. 109). Rare granitic pebbles have been noted in the Haupiri Conglomerates of the Nelson district (Bell, Webb, and Clarke, 1907, p. 46, 71); the age of the Haupiri rocks is not known but is possibly Silurian or even Cambrian. Granitic pebbles are abundant in the Permain sediments of the Clinton district (Ongley, 1939, p. 32) and in the Mesozoic conglomerates (Hokonui Facies of Wellman, 1952) of both islands (Marshall, 1904; Watters, 1952; Marwick, 1946; Bartrum, 1935).

This survey shows that granitic debris is present in varying amounts in sediments from possibly Precambrian age to late Mesozoic. As the Kahurangi Point to Ahaura River granite intrudes both the Ordovician Aorere Group as well as the Waiuta Group that is derived from granite, the evidence is conclusive that there are at least two granite formations—pre-Ordovician and post-Ordovician. The pre-Ordovician terrain is now possibly represented by gneisses in the Paparoa Range. Critical data are not available with which to correlate the other granites with post-Ordovician sediments containing granitic material. Some similarities have been noted between the granitic rocks in Fiordland and pebbles in the Permian and lower Mesozoic sediments in Otago (Turner, 1937-8, pp. 247-8).

Petrographic Correlation of the Granites

In north-west Nelson the soda-alkali granite characteristic of the Separation Point to Mt Murchison batholith is petrographically and chemically distinct from the alkali and calc-alkali granites typical of the more westerly belts. The chemical difference is shown clearly in the available chemical analyses, the Separation Point to Mt Murchison granite being a sodic type, the others the more common potassic varieties (Fig. 2). The significance of this difference is not clear. Whether it denotes an age difference must await a critical examination of the granitic pebbles in the Haupiri and Triassic conglomerates of Nelson; present information is that pink alkali and calc-alkali granite pebbles are present in the latter. The distinction between the two types of granite finds a counterpart in the difference between the potassic Greenland and Waiuta greywackes and the sodic upper Paleozoic and lower Mesozoic "Alpine Facies" greywackes (Reed, 1957). As both these groups of greywackes are derived from granitic terrains, the question arises whether they can be correlated with the granites. The potassic Kahurangi Point to Ahaura River granite, however, intrudes the potassic Waiuta sediments so that the only possible relation between the two would be the origin of the granite from the sediments, an unprofitable subject to pursue with present knowledge. Nor is it likely that the Separation Point to Mt Murchison granite was the sole source for the sodic Mesozoic "Alpine Facies" greywackes. The Kahurangi Point to Ahaura River and Paparoa Range to Kongahu Point granites are both potassic types, but the abundance of quartz porphyries with the latter may mean that they are of different origin and age.

Although in north-west Nelson there are at least two geographically and petrographically distinct types of granite, no such clear cut distinction is apparent in Fiordland and Stewart Island. No granite terrain similar to the Separation Point—Mt Murchison type is known; the closest mineralogically are perhaps the gneissic tonalites ("trondhjemites") and granodiorites ("oligoclase granites") of the Manapouri

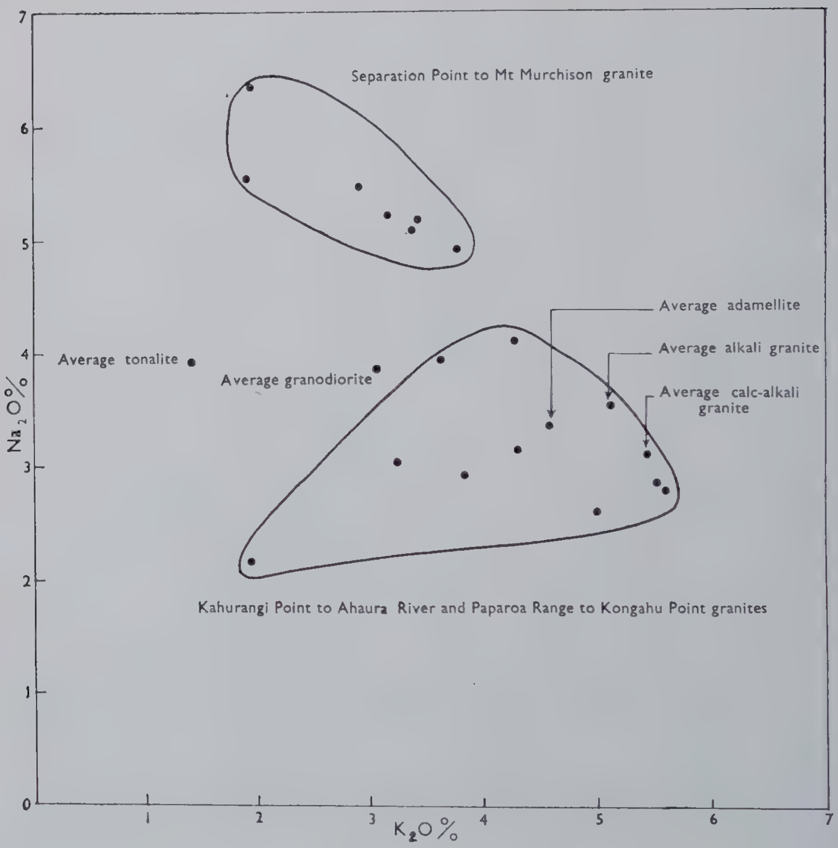

FIG. 2.—Weight percentages of soda and potash in Nelson granites showing sodic nature of Separation Point to Mt Murchison granite compared with Kahurangi Point to Ahaura River and Paparoa Range to Kongahu Point granites. The weight percentages of Nockolds' (1954) average alkali and calc-alkali granites, adamellite, granodiorite, and tonalite are included for comparison.

region (Turner, 1937-8). The majority of the granites in Fiordland and Stewart Island are alkali and calc-alkali granites that are tentatively correlated with the potassic westerly granitic belts in north-west Nelson. A major problem is that, whereas in Nelson Permian lavas and tuffs are probably invaded by gabbros, norites, and amphibolites that grade into the Separation Point to Mt Murchison granite, in southern areas apparently similar gabbros, norites, and amphibolites of the Clinton River, Longwood Range, Bluff, and northern Stewart Island (Park, 1921; Service, 1937) which also invade Permian volcanics and sediments, are associated with potassic rather than sodic granites. If the correlation of the basic rocks is correct, then either there is an undiscovered break between these basic rocks (and any equivalent to the Separation Point to Mt Murchison granite) and the bulk of the granite rocks in Fiordland and Stewart Island, or alternatively that there is no age difference between the sodic and potassic granites in Nelson, the Separation Point to Mt Murchison granite being merely an unusual variant that is absent in the southern areas. The age and relationships of the Separation Point to Mt Murchison granite thus constitute one of the major unsolved problems connected with the granite rocks in New Zealand.

Evidence from Mineralization

Mineralization related or possibly related to granite comprises minerals containing Au, Ag, W, Mo, Cu, Pb, Sb, Zn, Sn, Be, Ba, F, together with the gangue sulphides pyrite, arsenopyrite, and pyrrhotite. Of these only Au and W (scheelite) have had any real economic significance. Excepting gold, silver, and the sulphides, the distribution can be summarized:

Molybdenite—lodes at Mt Radiant, Paparoa Range, Reefton, Caroline Peak, Longwood Range (Willett, 1944), Stewart Island (Morgan, 1927, p. 70).

Wolframite—lodes at Port Pegasus, Waipori, Mt Mantell; alluvial in Paparoa Range (Morgan, 1927, p. 107).

Stibnite—Reefton, Paparoa, Owen, Otago, and Marlborough lodes.

Scheelite—Otago and Marlborough lodes; gravels on west coast.

Cassiterite—Port Pegasus lodes; gravels on west coast.

Barite—deposits at Thomson hill.

Fluorite deposits at Thomson hill and Stewart Island (Skey and McKay, 1890).

Beryl—pegmatites at Charleston, vein in Paterson Inlet.

Chalcopyrite—lodes at Mt Radiant, Paparoa Range, Reefton, Wilberforce River, Mt Rangitoto, Moke Creek, Waitahuna, Dusky Sound.

Galena—lodes at Owen and Wangapeka rivers, Mt Radiant, Victoria Range, Mt Rangitoto, Otago, Paterson Inlet and Bedstead Gully.

Study of this distribution reveals that no single mineral or group of minerals can be related to any one granite terrain or type. The distribution of molybdenite, wolframite, cassiterite, and beryl is evidence for the correlation of the Fiordland and Stewart Island granites with the two westerly belts in Nelson. Mineralization associated with the Separation Point to Mt Murchison granite are barite and fluorite, and possibly lodes in the Owen, Wangapeka, and Bedstead Gully regions, though these lodes could equally well be associated with the Kahurangi Point to Ahaura River granite. The occurrence of molybdenite in the basic rocks of the Longwood Range may indicate that they are coeval with the Fiordland granites. The lodes of the Otago and Marlborough schists contain minerals which are associated with granites elsewhere.

Relation to Regional Metamorphism

Progressive regional metamorphism in the Otago, Westland, and Marlborough schists is indicated by the index minerals—chlorite, biotite, oligoclase-garnet (Turner, 1938, Lillie and Mason, 1955). The schists of highest grade are now truncated by the Alpine Fault but comparison with progressive metamorphic sequences elsewhere indicates that if not faulted the highest grade rocks would grade through a sillimanite zone into granite (Harker, 1952, pp. 208-29). Thus irrespective of the origin of the Otago and Marlborough quartz lodes, it can be inferred that granite is closely connected with the regional metamorphism, and this remains valid irrespective of whether the granite is the end product of metamorphism or is the metamorphic agent. Support for the inference is provided by the occurrence of pegmatite veins in the high grade schists of Westland (Wellman, 1955, p. 16). This inferred granite is nowhere exposed in the Otago, Westland, and Marlborough schist, nor is there evidence linking any of the granites exposed elsewhere in New Zealand with the regional metamorphism. This raises two further problems, still undecided—the age of the rocks forming the schists and the age of their metamorphism. An upper limit to the age of the rocks is provided by the occurrence of fossils in the greywackes and argillites and volcanics near the schist margins. "These fossils are of different ages in different places; in Nelson and Southland, on the western margin of the schist belt, Permian or Carboniferous; on the east side of the schist belt, upper Triassic. Except for the gradual decrease in metamorphism there is no abrupt change in lithology from the schist into these fossiliferous sediments and no reason for suspecting an unconformity. Consequently the rocks that form the upper part of the schist are unlikely to be very much older than the adjoining fossiliferous rocks. Moreover, even the most altered of the schists has a chemical composition similar to the least altered and similar to that of the adjoining fossiliferous rocks of the middle division [upper Paleozoic-lower Mesozoic], but, in that thick quartzites and marbles are absent, different from that of many of the lower Paleozoic rocks of the lower division [lower Paleozoic]. Consequently the whole of the sediments that form the extensive schist belt may be Carboniferous to middle Triassic in age" (Wellman, 1952, p. 17).

There are three major hypotheses concerning the age of metamorphism: (i) Late Permian or early Triassic metamorphism; the semi-schistose condition locally developed in Triassic rocks is then attributed to subsequent movements (Turner, 1938, p. 161). (ii) Metamorphism during the early Cretaceous "post Hokonui" orogeny responsible for the folding of the Mesozoic rocks (Ongley, 1939, p. 32). (iii) Metamorphism related to period of maximum load or depth of

Age*	Rock Type	Distribution	Mineralization† Directly or probably related to granite	Possibly related to granite	Remarks
PRE-ORDOVICIAN *Precambrian?*	Granite and/or gneiss (inferred)	Paparoa Range gneiss?	—	—	Derived sediment in Precambrian (?) Waiuta and Greenland Groups.
POST-ORDOVICIAN	Alkali and calc-alkali granites, syenites, adamellites, granodiorites, tonalites, diorites, quartz porphyries.	Kahurangi Point to Ahaura River, Paparoa Range to Kongahu Point, Westland.	**Au**, *Mo*, *Cu*, *Sb*, W, Be, Zn, Pb	Sn	Intrudes lower Ordovician sediments. Reefton gold lodes. Paparoa Range to Kongahu Point granite with quartz porphyries possibly distinct type.
pre-Devonian? *and/or pre-Triassic?*		Fiordland Stewart Island	*Au*, *W*, *Sn*, *Cu*, Zn, Be, Mo, F, Pb	—	Intrudes lower Ordovician sediments. Possibly coeval, in part or whole with gabbros, norites, diorites, emplaced in Permian volcanics.
POST-PERMIAN	Soda-alkali granite alkali granite, syenite, diorite, gabbro, amphibolite.	Separation Point to Mt Murchison.	*Ba*, *F*, *Au*, *Pb*, Sb, Zn		Intrudes upper Ordovician sediments and probably Permain volcanics. Relation to previous group not known.
pre-Triassic? or *pre-Cretaceous?*	Granite (inferred)	Below Schist (not exposed except for pegmatites in highgrade schists)	—	**Au**, **W**, *Sb*, *Cu*, Pb	Gold and scheelite lodes in Otago and Marlborough schists. Inferred granite associated with metamorphism.
POST-TRIASSIC *pre-Cretaceous?*	Granite (hypothetical)	Below greywacke (not exposed)	—	*Au*, *Cu*	Quartz lodes in greywackes and argillites, some of which contain upper Triassic fossils, possibly related to unexposed granite.

*Age in capital letters reasonably certain. Likely age or alternatives in italics.
†Mineralization once economically important in bold type, minor deposits in italacs, remainder traces only.

burial which was probably early Cretaceous (H. W. Wellman, pers. comm.). Critical data to decide between these hypotheses are still lacking and consequently the age of the inferred granite associated with the metamorphism is also in doubt.

Conclusion

Definite statements as to the age of the granites and the related, or possibly related, mineralization in New Zealand are not warranted on the data available. Perhaps this will remain the position until radioactive dating methods are used. The present state of knowledge is summarized in Table I.

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NATURAL HEAT FLOW FROM THE THERMAL AREAS OF TAUPO SHEET DISTRICT (N 94)

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(Received for publication, 23 September 1957)

Summary

Heat flow from the thermal areas of Sheet District N94 has been estimated to be 274,000 kcal/sec ($3{,}910 \times 10^6$ B.Th.U./hr) above 0°C. The figure is based on measurements made during the period March 1951 to April 1952. The heat flow is equivalent to a loss of 24×10^{-6} cal/cm^2/sec over the whole area covered by the sheet. The heat flow could be produced by the flow upwards of 1,440 kg/sec of water with a temperature of 189°C.

Introduction

The Taupo Sheet District (N94) covers 436 square miles of the Rotorua-Taupo volcanic region described by Grange (1937). It includes the Wairakei area that is being developed for geothermal production of electricity. The main centres of thermal activity within the sheet are Ohaki, Wairakei Geyser Valley, Waiora Valley, Rotokaua, and the areas adjacent to the town of Taupo (see Fig. 1). Work was carried out in the field by Messrs C. J. Banwell and K. J. McCree, of Dominion Physical Laboratory, D.S.I.R., and Messrs A. C. M. Laing, J. Healy, and the writer, of N.Z. Geological Survey, D.S.I.R., during the period March 1951 to April 1952. The measurement of heat flow from the Wairakei area was summarised by Healey (1956, p. 218-20).

This paper is based on an unpublished report circulated in 1952, from which results were quoted by Banwell (1955, p. 50). Its purpose is to enable comparison with future measurements of heat flow. Banwell's figures for heat flow were discussed by Studt (1957).

All heat flows are expressed as heat above 0°C.

Methods of Estimation

The heat flow from hot springs and pools consists principally of the heat content of the water discharged, together with the heat carried off by steam evaporating from the water surfaces. The heat loss as water from the springs of a particular area has been

N.Z. J. Geol. Geophys. 1: 65–75.

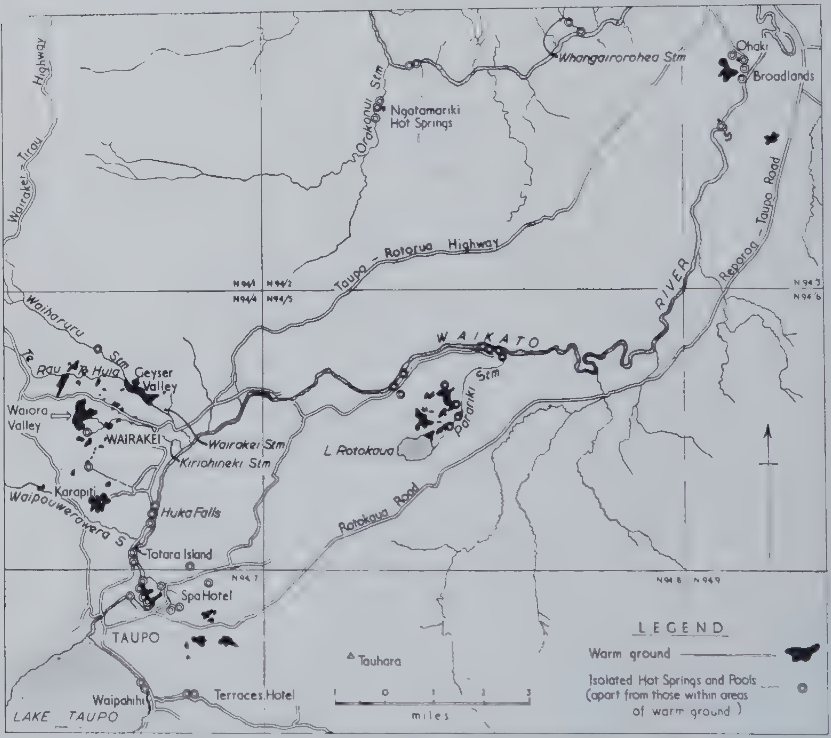

FIG. 1.—Taupo Sheet District, showing Thermal Areas.

arrived at by the summation of the estimated heat discharges of the individual springs, or by measuring the increase in heat content of a stream into which the springs discharge. The second method is to be preferred as it includes the heat loss represented by the undetected discharge of hot water. However, where hot springs discharge into a large river (Waikato), it has not been possible to use this method because of the difficulty of measuring the very small rise in temperature. Stream flows were estimated by measuring the surface velocity of the stream where its bed was fairly uniform, and its cross section. The heat loss represented by the discharge of steam from the surface of springs and pools has been estimated on the basis of a graph relating surface temperature to heat loss (Fig. 2). From 20° to 70°C the relationship is based on a formula given in the *International Critical Tables* (Washburn, 1929, p. 54), and above this temperature results experimentally determined by Mr Banwell have been used. A wind velocity of 2 m/sec, a barometric pressure of 760 mm, and a humidity of 100% at 10°C have been assumed.

The relationship used applies strictly only to pools whose surface is undisturbed, but, as the effect of bubbling is to increase the surface area and hence the steam output, it gives a minimum value.

There is undoubtedly a considerable discharge of hot water into the bed of the Waikato River where it flows through, or adjacent to, thermal areas. By taking values, which in some cases are only rough estimates, for the hydraulic gradient towards the river, the mean temperature of the seeping water, the wetted perimeter of the river, and an average porosity for the rocks adjacent to the river, and using figures given by Tolman (1937, p. 199) for the aver-

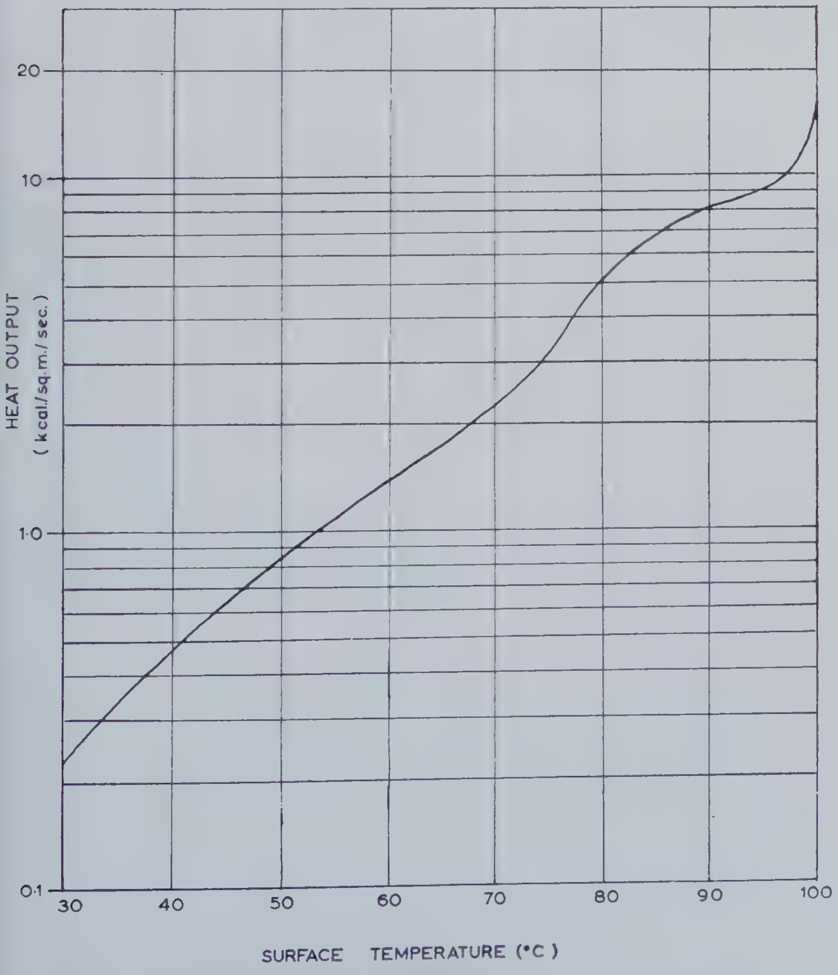

FIG. 2.—Heat Loss as Evaporation from a Water Surface.

age velocities of near surface ground water in various media under a 1% hydraulic gradient, it is possible to place an approximate figure on the heat loss to the river. This method was applied also to find the heat flow into Lake Taupo at Waipahihi.

For the computation of the heat output from steaming ground the calorimetric results of Messrs Healy and Banwell at Wairakei have been used. These workers divided the steaming ground within a test area into three groups, '*a*' with one steam vent per 10 sq ft and a heat output of 0·0103 cal/cm²/sec; '*b*' with one steam vent per 24 sq ft and a heat output of 0·00527 cal/cm²/sec; and '*c*' with no steam vents and a heat output of 0·00169 cal/cm²/sec (Mr J. Healy, pers. comm.).

The heat loss by conduction through the soil to the surface can be estimated by assuming reasonable values for the average soil conductivity and the average thermal gradient. A soil conductivity of 0·001 cal/cm/°C/sec has been assumed (see Birch *et al.*, 1942, p. 259), and a gradient of 1·0°C/ft has been applied to the areas surrounding thermal activity that are thought to be underlain by hot water. This gives a heat flow of 33×10^{-6} cal/cm²/sec. Although the thermal gradient assumed may be too steep for some areas, the heat flow by conduction through the soil is comparatively small, and an error in this figure will not greatly change the estimated total heat flow.

HEAT FLOW ESTIMATES

For the estimation of the heat flow from Sheet District N94, the area has been divided into the nine sub-sheets; these cover the same areas as the sheets of N.Z.M.S. 2 and 86 (see Fig. 1) .There is no known thermal activity within the sub-sheets N94/1, N94/6, and N94/9. Table 1 summarises the heat flow estimates for the individual thermal areas. Table 2 gives details of the assumptions on which the calculations of heat loss by seepage into the Waikato River and Lake Taupo are based.

Sub-Sheet N 94/2 (Whakapapataringa)

The main thermal area is at Ngatamariki hot springs which are on the banks of the Orakonui Stream about one mile from its junction with the Waikato River. A few small warm springs are found on the left bank of the Waikato and there are two hot pools on the Whangairorohea Stream. There is little warm ground; two small patches occur on the river terrace to the east of the Ngatamariki springs. The main heat flow is represented by the increase in temperature of the Orakonui Stream where it flows past the Ngatamariki thermal area. The stream had a flow of about 1,700 l./sec and the temperature increased by 4·5°C. There is probably some seepage

TABLE 1.—Heat Flow from Thermal Areas of Sheet N94 (kcal/sec).

Sub-Sheet	Thermal area	Heat from Hot Springs		Heat from warm ground	Heat as seepage to rivers	Conductive heat loss	Totals
		as water	as steam				
N 94/2	Ngatamariki	9,800	2,800	0	0?	0	*12,600*
N 94/3	Ohaki	1,000	8,100	3,700			12,800
	Broadlands	0	200	2,500			2,700
	Sub-sheet Total	1,000	8,300	6,200	7,200	400	*23,100*
N 94/4	Geyser Valley	24,700	9,300				34,000
	Waiora Valley	3,300	16,800				20,100
	Miscellaneous	14,800	2,600				17,400
	Sub-sheet Total	42,800	28,700	55,000	18,400	5,100	*150,000*
N 94/5	Rotokaua	3,900	17,100	16,100	14,400	600	*52,100*
N 94/7	Spa	3,400	2,100	4,000	7,200		16,700
	Waipahihi	100	0	0	1,500		1,600
	Terraces	1,600	1,300	0	0		2,900
	Miscellaneous	0	0	12,600	0		12,600
	Sub-sheet Total	5,100	3,400	16,600	8,700	2,100	*35,900*
N 94	*Totals*	62,600	60,300	93,900	48,700	8,200	*273,700*

of hot water directly into the Waikato River within this sub-sheet, but no estimation of the heat loss represented by this has been attempted.

Sub-Sheet N 94/3 (Rautawiri)

This sub-sheet includes Ohaki and Broadlands thermal areas; they lie on opposite sides of the Waikato River. There is an area of 370,000 sq m of warm ground associated with the hot springs. Although some of the warm ground contains many steam vents depositing sulphur, the main part contains no vents and an average heat flow of 0·00169 cal/cm^2/sec has been assumed. There is no water discharge from the Broadlands area and the discharge from Ohaki was only 11 l./sec. The heat loss by seepage of warm water to the Waikato River has been estimated, and the assumptions made in the calculation are set out in Table 2. A conductive heat flow of 33×10^{-6} cal/cm^2/sec over an area of half a square mile has been included.

Sub-Sheet N 94/4 (Wairakei)

The most extensive areas of thermal activity within this sub-sheet are Geyser Valley and Waiora Valley. It also includes the area in which geothermal steam is being developed for the production of electricity (see Grange, 1955). There are other areas of steaming ground and hot springs along Te Rau te Huia Stream, Waiharuru Stream, Waipouwerawera Stream, and near Karapiti Blowhole. Minor hot springs discharge into the Waikato River about Huka Falls and Totara Island.

The heat flow as water from the springs of Geyser Valley is based on flow measurements made on Wairakei Stream at the upper and lower ends of the valley on 12 October 1951. The upper flow was 880 l./sec at 22·85°C, and the lower flow 1,130 l./sec at 38·75°C. This gives a heat output of 23,700 kcal/sec, and to this has been added the heat flow as water from springs along the stream outside the points of measurement, giving a total of 24,700 kcal/sec. The heat flow as water from individual springs in the valley was estimated and this gave a total heat flow of 21,200 kcal/sec. Considering the uncertainties of measurement, and that some water may be discharged into the stream undetected, the agreement is considered reasonable.

The heat flow as water from Waiora Valley is based on a measurement made on 31 August 1951 on Kiriohineki Stream which drains the valley. A flow of 76 l./sec at 44°C gave a heat output of 3,300 kcal/sec. The heat flow down Waiharuru and Te Rau te Huia Streams was estimated as 11,000 kcal/sec, and that down Waipouwerawera Stream as 3,200 kcal/sec.

There are 1,300,000 sq m of warm ground in the sub-sheet, and assuming a heat flow of 0·004 cal/cm^2/sec, this gives a heat loss of 52,000 kcal/sec. To this has been added 3,000 kcal/sec for the output of Karapiti Blowhole (Wilson, 1955, p. 29).

TABLE 2.—Heat Flow as Seepage into Waikato River and Lake Taupo.

Sub-Sheet	Temp. rise (° C)	Dimensions of area of discharge		Hydraulic gradient (%)	Porosity (%)	Velocity for 1% gradient (ft/day)	Heat flow (kcal/sec)
		Length (ch)	Width (ft)				
N 94/3	20	200	75	0·5	35	6·33	7,200
N 94/4	20	170	75	1·5	35	6·33	18,400
N 94/5	20	200	150	0·5	35	6·33	14,400
N 94/7 (Waikato)	50	48	150	3·2	25	1·16	7,200
N 94/7 (Taupo)	50	60	10	1·0	35	6·33	1,500

TABLE 3.—Heat Flows, Enthalpies, and Mass Discharges for Sub-Sheets.

Sub-Sheet	Heat flow as water (kcal/sec)	Heat flow as steam (kcal/sec)	Total heat flow (kcal/sec)	Heat flow (cal/cm²/sec)	For discharge at 100° C	
					Mass discharge (Kg/sec)	Enthalpy (cal/g)
N 94/2	9,800	2,800	12,600	10·1 × 10−6	102	123
N 94/3	8,600	14,500	23,100	18·5 × 10−6	109	212
N 94/4	66,300	83,700	150,000	120 × 10−6	794	189
N 94/5	18,900	33,200	52,100	41·6 × 10−6	241	216
N 94/7	15,900	20,000	35,900	28·7 × 10−6	190	189
N 94	119,500	154,200	273,700	24·3 × 10−6	1,436	191

The heat loss by seepage into the Waikato River has been estimated under the assumptions set out in Table 2. A conductive heat loss over an area of 6 square miles has been included.

Sub-Sheet N 94/5 (Rotokaua)

The Rotokaua thermal area is included in this sub-sheet. The lake is drained by the warm Parariki Stream, which discharges about 150 l./sec into the Waikato River; the stream represents an estimated heat loss of 3,800 kcal/sec. Warm ground covers an area of 403,000 sq m, much of which contains active steam vents depositing sulphur. For this warm ground a heat flow of 0·004 cal/cm^2/sec has been assumed. Along the banks of Waikato River there are many places where hot springs discharge into the river. The heat loss by seepage of hot water into the river has been estimated; the calculation is in part based on measurements of temperature and hydraulic gradient made during the investigations for the proposed Parariki dam site. A conductive heat flow over an area of three-quarters of a square mile has been included.

Sub-Sheet N 94/7 (Taupo)

The sub-sheet covers the thermal areas adjacent to the town of Taupo. The main hot springs areas are at the Spa Hotel (Otumuheke), the Terraces Hotel (Onekeneke), and along the shore of Lake Taupo at Waipahihi. There are patches of warm ground between the town and Tauhara mountain. Part of the town of Taupo is underlain by warm water and this is tapped by drill-holes. The warm ground within the sub-sheet covers 415,000 sq m, and a heat flow of 0·004 cal/cm^2/sec has been assumed. The heat loss into the Waikato River at the Spa thermal area, and into the lake at Waipahihi, has been estimated. A conductive heat loss over an area of 2½ square miles has been included.

Sub-Sheet N 94/8 (Tauhara)

This sub-sheet includes a small patch of steaming ground on the Taupo-Napier highway (Grange, 1937, p. 100), but the heat output from this is relatively insignificant. Taupo residents have mentioned to the writer an area of warm ground to the south of the Taupo-Napier highway, but this could not be located.

Total Heat Flow for Taupo Sheet District

The heat flow figures for each sub-sheet and the totals are listed in Table 3. The total natural heat output from the thermal areas of the sheet was approximately 274,000 kcal/sec, or 3,910 × 10^6 B.Th.U./hr. Using the figure given by Grange (1955, p. 14) of 30,000 B.Th.U./hr being equivalent to 1 kW of generated power, this gives a power potential of 130,000 kW.

DISCUSSION

If it is assumed that the discharge of steam and water takes place at 100°C, it is possible to calculate the mass discharge that would be necessary to carry the measured heat flows. From these figures and that for the total heat flow the average enthalpy for the total mass discharged can be calculated. The mass discharge and enthalpy figures for each sub-sheet and for the sheet as a whole are given in Table 3. The enthalpy for sub-sheet N94/2 is much lower than for the other sub-sheets and probably is the result of extensive mixing of the ascending hot water with cold ground water. For the other sub-sheets the enthalpies all lie between 189 and 216 cal/g; the underground hydrothermal conditions within these sub-sheets are probably similar. The total heat flow could be produced by the flow upwards of 1,440 kg/sec of water with a mean enthalpy of 191 cal/g, that is, a temperature of 189°C.

The heat output as water, 119,500 kcal/sec, all reaches the Waikato River, and, assuming a mean flow of 85,000 l./sec, would raise the temperature of the river by 1·4°C. Because of practical difficulties no accurate measurement has been made of the rise in temperature of the Waikato between Lake Taupo and where it flows out of the area covered by sheet N94.

The heat flows expressed in cal/cm²/sec for each sub-sheet and for the whole area are given in Table 3. They show that the heat flow per unit area for the Wairakei sub-sheet is almost five times the average heat flow for the Sheet District as a whole. A figure of $1 \cdot 3 \times 10^{-6}$ cal/cm²/sec has been calculated for the heat flow to the surface of the earth, based on measurements in South Africa and Great Britain (Birch, *et al.*, 1942, p. 268); this is one nineteenth of the average heat flow from the thermal areas of sheet N94 (taken over the whole area covered by the sheet).

Ellis and Wilson (1955) have calculated the heat output of the Wairakei sub-sheet from measurements of chloride content of the waters in 1954. Their figure for the heat flow was 144,000 kcal/sec measured above 12°C, and of this about 62,000 cal/sec was being discharged from steam wells. The present writer's calculations of heat flow adjusted to the 12°C reference temperature gives a figure of about 140,000 kcal/sec. As by 1954 the steam wells had started to produce a noticeable decrease in the natural thermal activity, the agreement is considered good.

Figures for the heat flow from other thermal areas are given in Table 4. These have been adjusted to a reference temperature of

TABLE 4.—Heat Flow from Thermal Areas (above 0° C except where stated).

Area	kcal/sec	Reference
White Island, N.Z. (steam)	290,000	Wilson, 1939
Taupo Sheet District	274,000	
Yellowstone Park (water only)	236,000	Allen and Day, 1935 : 136
Iceland (water only)	160,000	Barth, 1950 : 29
St Vincent, B.W.I. (above 24° C)	18,000	Robson and Willmore, 1955
Dominica, B.W.I. (above 24° C)	17,000	Robson and Willmore, 1955
Ketetahi, N.Z. (steam)	14,000	Wilson, 1939

0°C, except for the figures of Robson and Willmore (1955) which are for heat above 24°C. The heat flow as water from the thermal areas of Taupo Sheet District amounts to 119,500 kcal/sec; this is just over one-half of that estimated by Allen and Day for Yellowstone, and two-thirds of Peterson's estimate for Iceland. It is likely that the total heat flow from the thermal activity of the Taupo-Rotorua volcanic region is more than twice the heat output from Taupo Sheet District (see Grange, 1955, p. 14).

ACKNOWLEDGEMENTS

Thanks are expressed to Mr C. J. Banwell, Dominion Physical Laboratory, and Mr J. Healy, N.Z. Geological Survey, for the use of unpublished results on steam flow from pools and warm ground.

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GEOLOGY OF THE WAKARARA RANGE, CENTRAL HAWKE'S BAY

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Summary

The Wakarara Range is a greywacke piercement body flanked on the western and southern sides by faults, and on the eastern side by steep-dipping upper Pliocene rocks. The range is separated from the main greywacke block of the Ruahine Range by a long narrow graben—the Ohara depression. Marine sedimentation in the Ohara depression started at least as early as middle Pliocene (lower Waitotaran) and continued until early Pleistocene (lower Nukumaruan) time, when the sea regressed and thick sequences of conglomerates were deposited on a truncated surface of Waitotaran rocks. The Wakarara piercement body emerged in latest Waitotaran time; the southern part rose above sea-level first. Movement of the Wakarara block as a whole took place in a southerly direction.

Introduction

The gathering of geological data on the Wakarara district was started in October 1949, when the author accompanied Dr D. A. Brown, now of University of Otago, on a brief trip across the range to get preliminary information for mapping the area immediately east of the range. Since that date, short, sporadic visits have been made to the area with Ministry of Works soil conservators, officers of both the New Zealand Forest Service and Lands and Survey Department. The area was again visited early in January 1957, when the author, accompanied by Messrs. G. C. Shaw, geologist; R. Jackson, forester; A. J. Mabbett, and O. T. Kingma, made final field observations to complete this account.

Topographic Setting

The Wakarara Range, together with Big Hill, occupies the eastern third of sheet N.Z.M.S. 1, N133 (unpublished) and extends for some 5 miles into the more southerly situated Sheet N140, (Fig. 1). The range is 12 miles long and 4 miles across at its widest part, which is 3,300 ft in height. The range is separated from the Ruahine Range by the long narrow Ohara depression, which runs northwards in between

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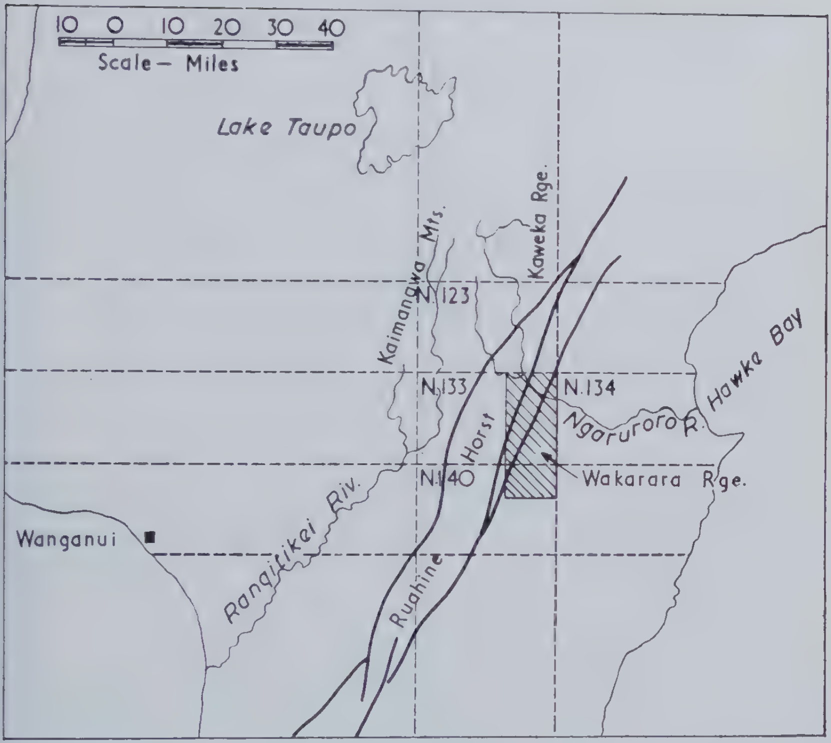

FIG. 1.—Locality map showing area described and main topographical features.

Big Hill and the northern end of the Ruahine Range (Figs 4, 11), where it joins the Kohurau Graben (Kingma, 1957a).

The Ohara depression is drained by the Ohara river system which, together with the Poporangi Stream, joins the Ngaruroro River east of Big Hill. The Ngaruroro River cuts through Big Hill, the gorge being 1,300 ft deep. The Makaroro River is antecedent and cuts through the southern end of the Wakarara block.

Two important transcurrent faults systems, the Ruahine and Mohaka fault systems, run through the area limiting the Ohara depression (Fig. 2), faulting in the Wakarara block proper is common, but not of major importance.

Extensive terracing has taken place, both on the western and eastern sides of the range, where both high and low terraces occur.

When viewed from a distance, particularly from the west, the silhouette of the range exhibits two distinctly different sky-lines. North of Duff's Valley the sky-line is smooth and with little relief, southward the outline is saw-toothed and sharp.

PREVIOUS GEOLOGICAL WORK

McKay (1877) visited the range in February 1877, and observed the differences in topography south and north of Duff's Valley, the southern part rugged, severely eroded, and with sharp peaks, the northern part with long north-sloping, flat-surfaced spurs which convey the impression of their being the original surface of a plane of denudation (Fig. 7). He also mentioned the presence of small outliners of shell limestone on these surfaces. McKay thought the rocks of the Wakarara Range to be younger than the rocks at Ngaruroro gorge immediately west of Big Hill.

Kingma (1957a) described the region along the continuation of the Ruahine fault system immediately north of the Wakarara—Big Hill area. General observations by Ongley (1933) and Waghorne (1927) were discussed (Kingma, 1957a, p. 344).

EROSION

The stream systems that drain the Wakarara Range are all shingle carriers and exceedingly large amounts of greywacke gravel are being transported. The amount of shingle transported by the Poporangi Stream, for instance, even during minor floods, has to be seen to be believed. The bare and heavily eroding greywacke ridges will probably continue to provide a vast supply of erosion products. The amount of shingle transported is so great that, in the writer's opinion, the Poporangi and Ohara streams are the main shingle-producing arteries in the Ngaruroro catchment, and as such the greatest threat to the Napier-Hastings Plain. This emphasizes the need to investigate the interaction between the animals and the vegetation in this catchment to assess the factors influencing erosion.

STRATIGRAPHY

The most complete section through the Plio-Pleistocene beds has been found on the eastern side of the Wakarara Range, in the gorges of the Poporangi Stream (Fig. 3). Lower Pliocene strata are absent, and the upper Pliocene (Waitotaran) beds rest immediately on the greywacke In localities where the lower Waitotaran sand and siltstones are absent the upper Waitotaran limestone forms the lowest Tertiary rocks. On the eastern side Nukumaruan marine strata conformably underlie Castlecliffian and Hawera terraces.

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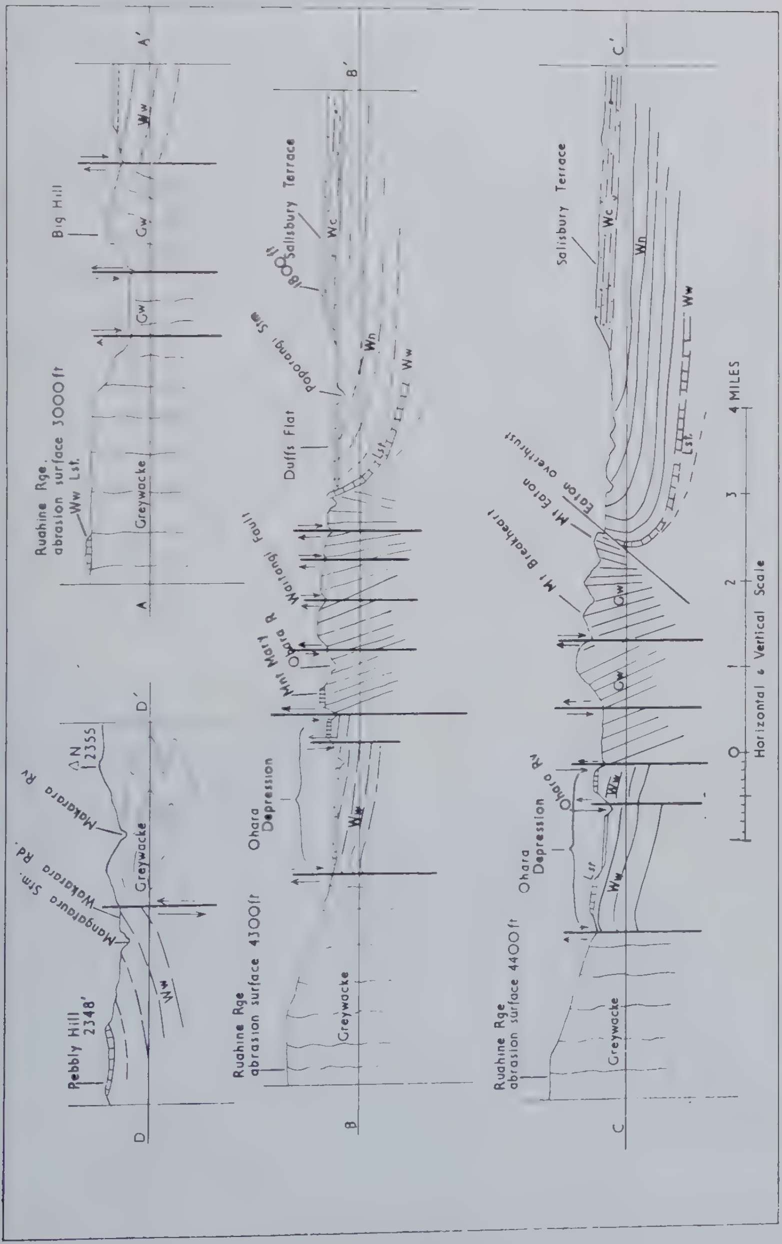

FIG. 3.—Cross-sections through Wakarara District.

The following is a generalized stratigraphical column:

N.Z. Series & Stages	Lithology	European equivalents	
Recent	lowest terraces and river debris	greywacke gravels, sands, silts	Holocene
Hawera	low terraces high terraces		upper Pleistocene
Castlecliffian	highest terraces		
Nukumaruan	Marine, blue-grey fossiliferous siltstones and sandstones; greywacke conglomerates		lower Pleistocene
Waitotaran	shelly, limestone at top, fossiliferous sandstone and siltstone		upper Pliocene
	Unconformity		
stage uncertain	indurated, alternating sandstones (grits) & siltstones (greywacke)		? Jurassic

Greywacke

The oldest rock in the district comprises unfossiliferous, indurated, alternating sandstones and siltstones, typically geosynclinal and usually termed greywacke. The sandstone beds exhibit mircro-banding $\frac{1}{20}$ to $\frac{1}{10}$ in. thick; where exposures are favourable scour casts may be observed along the base of the beds. The apices of the scour casts point east-south-east, which indicates that the sediments were derived from that direction (Kingma, 1958). The greywacke throughout the area is perfectly bedded and a consistent 040° strike has been observed. In the eastern part of the range, the beds dip steeply to the west, but westward through the range this dip changes rapidly to 70° east. The implications of this change are discussed under "structure".

Taking the effect of faulting into account, the thickness of the sequence is deduced to be of the order of 15,000 ft. A Jurassic age is postulated for these rocks which are less indurated than the greywackes of the Ruahine Range, for which a Triassic age is postulated; the strike, which appears to be of regional significance, suggests that they are equivalents of rocks of Jurassic age in the Eketahuna Subdivision (Ongley, 1935).

Although zeolite veining occurs, it has not been observed in the banded sequence; it is confined to the crushed rock in fault zones and as such, not a reliable indicator for rank.

Waitoaran Strata

The Waitotaran stage is important as it contains strata which are widespread and from which data for the reconstruction of the paleogeography has been derived. Two distinct and completely different lithologies form the stage. Where Waitotaran beds have been observed in contact with greywacke, the greywacke surface has been well peneplained before the Waitotaran sequence was deposited. The differences in thicknesses of the stage indicate that block movements of the greywacke undermass were in progress during the Waitotaran.

The lower Waitotaran comprises brownish, fine to medium grained sandstones, and blue-grey siltstones usually well bedded, with layers of shells and sporadic greywacke grit bands. These grit bands occur more commonly in the southern part of the district and are usually adjacent to the greywackes. In some places the arenaceous sequence reaches a thickness of at least 4,000 ft. The lower Waitotaran in the Ohara depression consists solely of blue-grey, sandy siltstones with shell bands and shell grit scattered through the rock; these siltstones form the gorge walls along the course of the Ohara River (Fig. 4).

The upper Waitotaran is characterized by shelly limestones (Figs 4, 5), the rock consists exclusively of pulverised shell material and

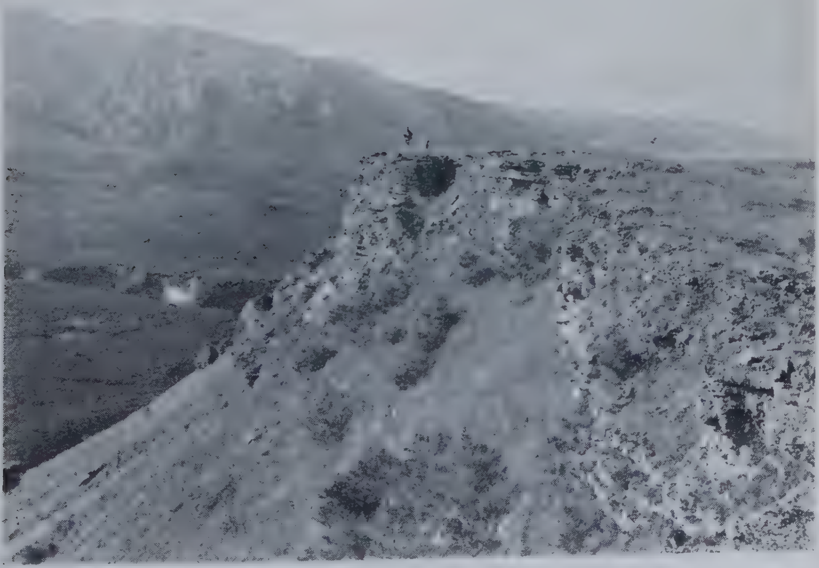

FIG. 4.—Limestone escarpment south of Mount Mary, escarpment slope facing west. Ruahine Range in background with flat surface on distant part. Ohara depression between limestone escarpment and Ruahine Range showing east-dipping Waitotaran siltstones in stream gorges. —Photo, G. C. Shaw.

is thus coquina. In some localities, particularly in the southern part of the district greywacke pebbles are incorporated. The western flank of the limestones of the Yeoman Syncline is characterised by fine greywacke grit, and the eastern flank by coarse (2 to 3 in.) debris. Increase in pebble size towards the southern Wakarara observed in the limestones of the eastern flank and on Pebbly Hill indicates that part of the southern Wakarara Range was above sea-level at the time.

The limestone can be traced northward into the Kohurau district, where it contains *Phialopecten triphooki* (Zitt.) and *Ostrea ingens* (Zitt.) and is considered to be of Waitotaran age (Kingma, 1957a). The limestone is very uneven in thickness, varying from 60 to 70 ft on the eastern side of the range and up to 150 ft on the western side.

Nukumaruan Strata

Throughout the district the Nukumaruan strata are distinctly arenaceous; no limestones occur. The typical Nukumaruan sediment is a blue-grey, fossiliferous, silty sandstone. Close to the range grits and fine conglomerates appear as thin (6 to 10 in.) layers in the siltstone. Particularly in the Eaton overthrust area greywacke chips are conspicuous in the Nukumaruan strata; they peter out rapidly away from the range and fade into the characteristic blue-grey, fossiliferous siltstone. Some major widespread conglomerate bands, however, have also been encountered, particularly in the sequence east of Big Hill, where they reach a thickness of 40 to 50 ft.

The Nukumaruan sediments overlie the Waitotaran limestone, the boundary being rather sharp. The base of the Nukumaruan is sandy with shell grit, but grades rather abruptly into the common blue-grey fossiliferous siltstones. These fossiliferous beds have been traced eastward into N.Z.M.S.1, N134, where their Nukumaruan age (Dr. C. A. Fleming, pers. comm.) is well established from Mollusca collections G.S. 5178, 5436-42, 5593, 5758, 5770, 6976.

Only in one area has it been possible to study the top of the Nukumaruan stage. East of Duff's Valley the stage grades into Castlecliffian sands and gravels. The top of the Nukumaruan becomes sandy and fossiliferous, indicating the approach of terrestrial conditions, under which the Castlecliffian in the area was laid down. The base of the Nukumaruan has been studied there only where Waitotaran limestones crop out and the thickness of the stage can only be assessed; it is at least 5,000 ft.

The very great thickness of the lower Pleistocene strata in this area shows that considerable differences in sea depths existed at the time the deformation took place, after the deposition of the Waitotaran limestones. The sediments were not only derived from the eroding greywackes of the North Island Geanticline (Kingma, 1957b), but also from land that is deduced to have existed at the time further east, in Hawke's Bay. The fine-grained sediments being eroded there formed the main source for the Nukumaruan sedimentation.

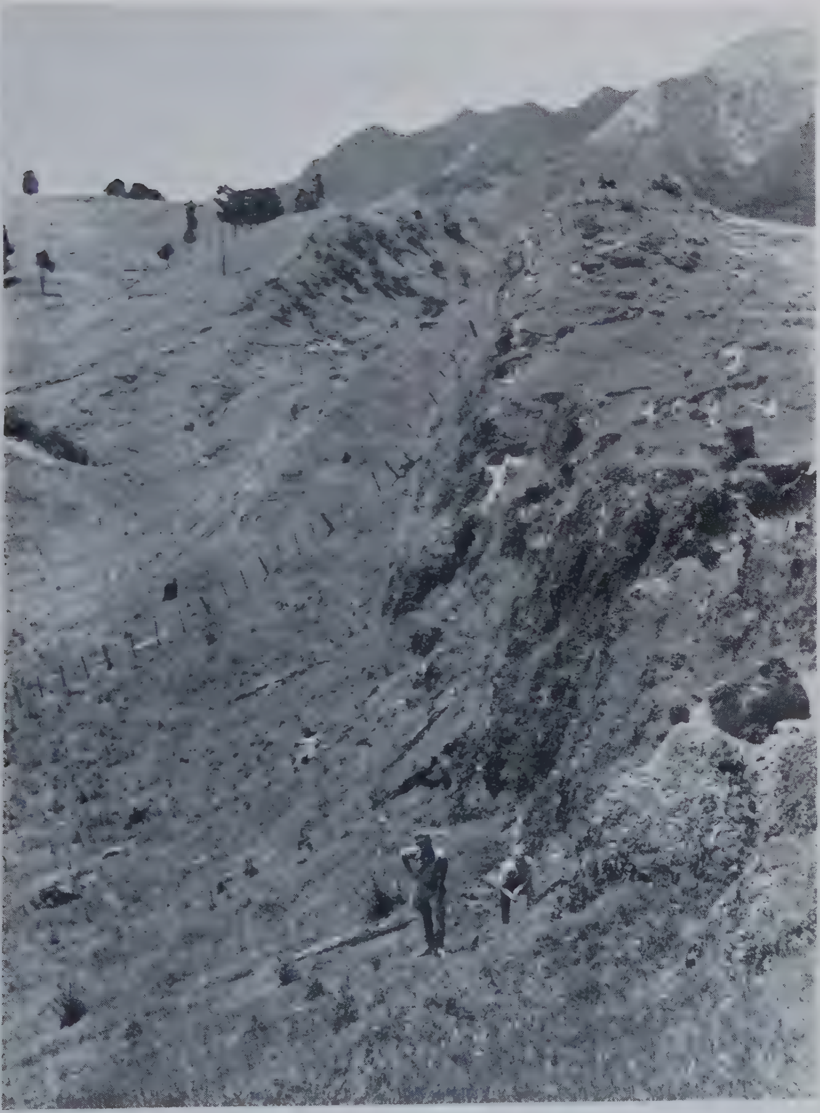

FIG. 5.—Waitotaran limestones dipping 70° west in the eastern limb of Yeoman Syncline.

—*Photo, G. C. Shaw.*

Castlecliffian Strata

Castlecliffian strata have been observed in the highest terrace in the south-east corner of the district. Although no fossils have been found in these terraces in the Wakarara district, a Castlecliffian age is postulated as the terrace grades eastward (east of area shown in Fig. 2), into marine, fossiliferous strata in which a Castlecliffian fauna has been found, G.S. 5378-9 (Dr. C. A. Fleming, pers. comm.) and which overlie fossiliferous sediments carrying an upper Nukumaruan microfauna F. 8064, 8079. The flat surface on these strata is called the Salisbury terrace; its surface dips 5° to the east and is extensively dissected.

The components of the Salisbury terrace are layers of silts and sands irregularly alternating with greywacke gravels. The sands are very pumiceous, but continuous, fairly pure pumice layers are rare; otherwise the bedding is typically fluviatile. The greywacke pebbles are weathered and disintegrate readily under the hammer. The sequence is about 500 ft thick.

The Salisbury terrace lies exactly opposite the highest point of the Wakarara Range and as that part of the range is most deeply eroded, its erosion products are probably entirely responsible for the building of the Salisbury terrace. Equivalents of the Salisbury terrace are found further south in the Ruataniwha plain. On the western side of the Wakarara Range remnants of a very high terrace have been found in the Ohara Valley, they are situated along the western part of the valley and dip away from the Ruahine Range. They are most probably correlable with the Salisbury terrace.

The well-cemented grit bands and limestone conglomerates at the eastern foot of the northern segment of Big Hill were deposited during the breaking up of the Waitotaran limestone cover. They abut Waitotaran strata at the western foot of The Fort (Trig. 4A, 1,844 ft). It is suggested that they are considerably younger than Waitotaran. If they were of Nukumaruan age, other Nukumaruan strata would crop out and Waitotaran debris would be incorporated in the Nukumaruan strata. A Castlecliffian age seems to be the most reasonable.

Hawera and post-Hawera Strata

Terraces, lower than the Castlecliffian Salisbury terrace, are widespread and may be divided into two groups. The term "group" is used here because terrace levels vary slightly, but not sufficiently to be a criterion for individual separation. These terraces are less tilted than the Salisbury terrace. They invariably occur at a lower level than the Salisbury terrace, and their height should therefore be informative as to their position in time. Both groups contain similar material, but there is no layering. Between the Wakarara Range and Big Hill the surface of the oldest group is about 1,500 ft above sea-level. The surface of the younger group is some 400 ft lower and occupies most of the area along the Poporangi Stream.

The lower terraces in the Ohara Valley belong to this group. They are, however, so extensively eroded that the mapping of the remnants would be a major work and beyond the scope of the present paper. For the purposes of mapping, the terraces in the Ohara Valley have therefore not been separated. All the Hawera terraces are aggradation terraces and were built after a degradation period. The Salisbury terrace must have covered an appreciably larger area immediately before uplift affected it. It was cut down and then built up again to form the Hawera terrace. The Hawera terrace does not show the same layering as the Castlecliffian terraces. The younger Hawera terraces were formed from older Hawera and Salisbury terraces by an identical process. These terraces have a maximum thickness of 50 ft and lie unconformably on the underlying, marine strata (Fig. 6).

The lowest group of terraces along the streams, and the present river rubble, belong to the post-Hawera deposits. Gorges more than 200 ft deep have been cut since the deposition of the last Hawera terrace. The deposits are at present being derived from the greywackes and from all the previous terraces; the amount of rock debris is so great that river-bed levels rise rapidly, particularly if floods are not of sufficient energy to remove shingle.

The occurrence of gravels along the Waitangi fault (Waitangi Stream) is of particular interest. They were deposited in a faulted valley, which probably came into existance through tensional forces (see below). The contact between the gravels and the Tertiary beds is irregular and in places the gravels are over 200 ft thick.

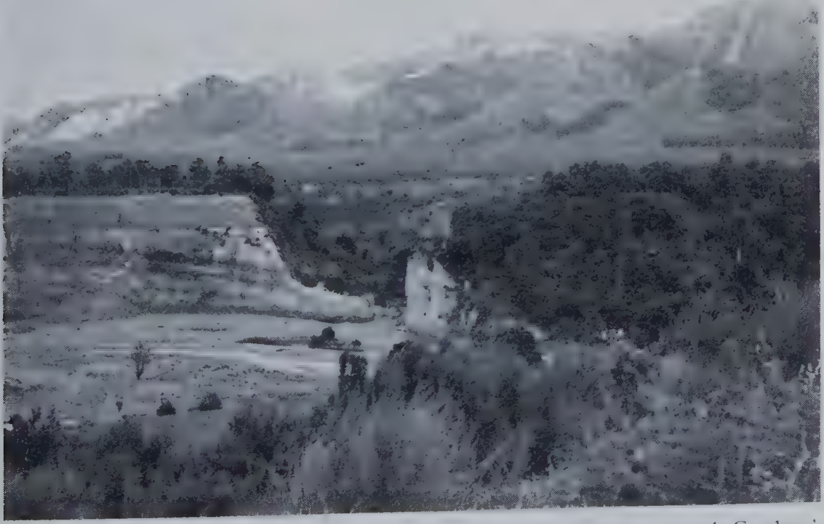

FIG. 6.—Makaroro River immediately downstream from Yeoman and Gardner's Saw Mill, Wakarara. Waitotaran sandy siltstones, dipping 15° east in river bank. Waitotaran siltstones covered by 50 ft of gravels. Almost completed break-through of Ellis Stream meander into Makaroro River; Wakarara greywackes in background. —*Photo, G. C. Shaw.*

STRUCTURE

The Greywacke Undermass Surface

The greywacke undermass surface (Kingma, 1957a) is very conspicuous in the Wakarara district and is also exposed on the Ruahine Range, on the eastern slope of Big Hill, and on the northern part of the Wakarara Range, although there it has been broken up into a series of long narrow blocks by faulting parallel to the general north-east grain (Figs 2, 3, 7, 10).

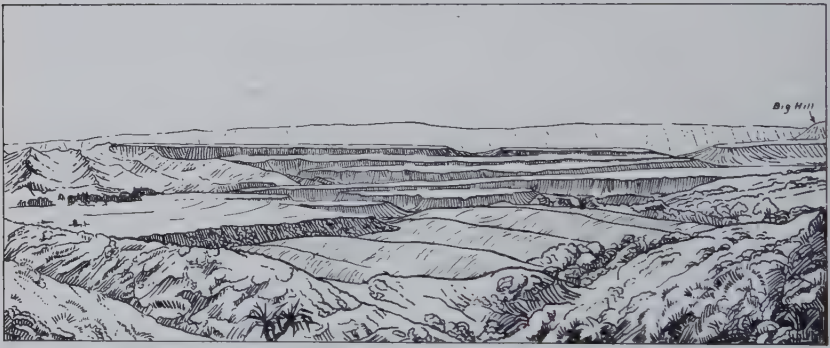

FIG. 7.—Sketch of remnant abrasion surfaces (Kaukau) on northern end of Wakarara Range.

Patches of Waitotaran limestone are still to be seen on the greywacke undermass surface in the northern Wakarara Range (Figs 2, 9). This feature has also been observed by Mr L. Masters of Hastings (pers. comm.) from the northern end of the Ruahine Range, and recently confirmed by Mr N. L. Elder of Havelock North (pers. comm.). The greywacke undermass surface in the northern part of the Wakarara Range dips to the north-west in a block called the "Mangleton" and disappears underneath Waitotaran siltstones. This is the only locality where the abrasion surface has been seen in contact with the siltstones and it appears that the abrasion surface continues underneath the siltstones without a break. The greywacke undermass surface was probably continuous in pre-Waitotaran time, at least in this area. As the base of the Tertiary in the Ohara depression has not been observed the nature of the greywacke surface there is not known.

In a recently published account of the geomorphology of the Hutt Valley, Stevens (1957) summarizes the setting of the Kaukau surface in the Wellington district. The present author considers that the extension of the Kaukau surface northward to identify it with the abrasion surface on the Tararua, Ruahine, and Wakarara ranges is not inconsistent with the available evidence. Both the abrasion sur-

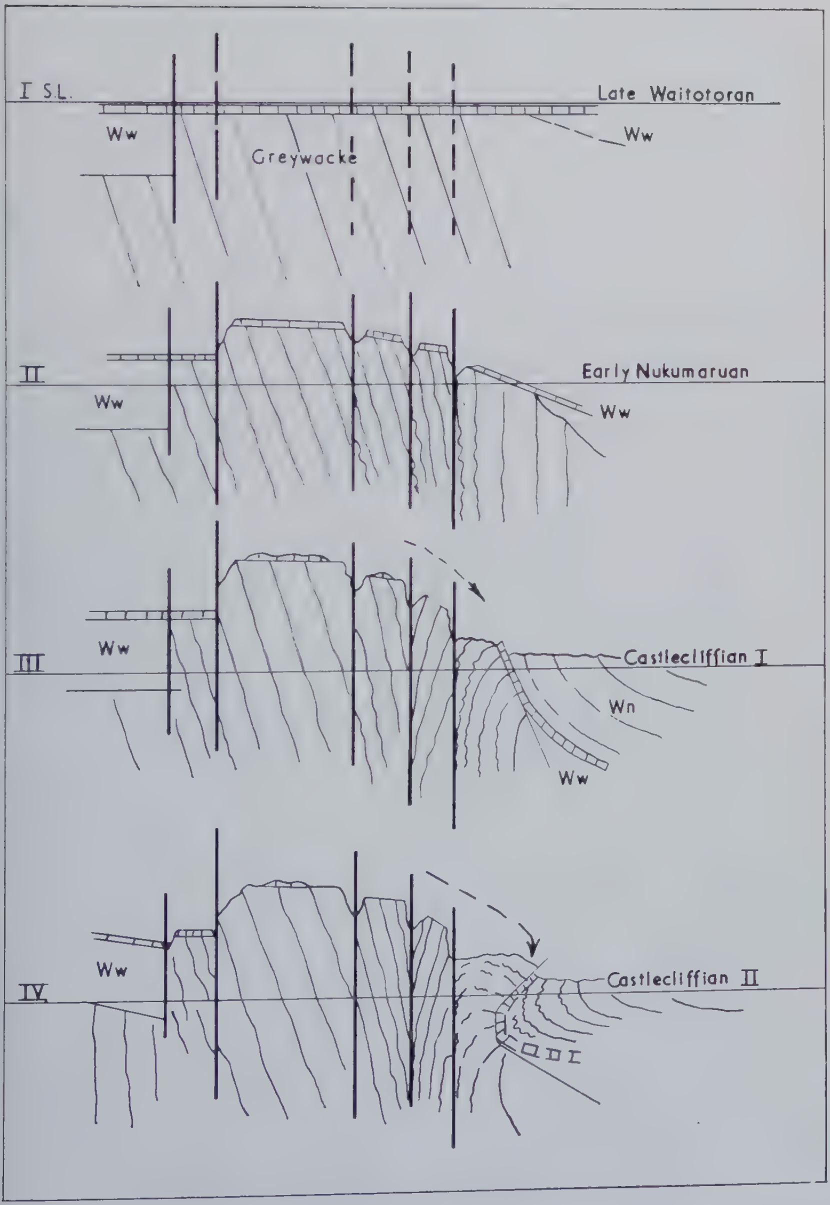

FIG. 8.—Sketched cross-sections through Wakarara Range showing history of block movements and attitudes of Kaukau surface. Sections III and IV suggest an explanation of the attitudes of the limestones on the eastern side of the range.

face and the Kaukau surface are major geomorphological features and obviously have taken considerable time to form; both started to form at approximately the same time and both occur on one and the same Horst (Kingma, 1957c). The name Kaukau surface is therefore extended to include the greywacke abrasion surface in Central Hawke's Bay.

The Wakarara Block

The Wakarara block (Figs 2, 3, 8, 9) faulted on the western and southern sides respectively by the Mohaka and the Mangataura fault systems, and with upturned limestones on the eastern flank, is typically a piercement structure. During the rise of the block, folding of Waitotaran and Nukumaruan strata around its southern end took place. Such folding did not take place around its northern end, on the contrary, the infaulted gravels in the Waitangi fault zone, the different attitudes of the Kaukau surface in the Waitangi and Mangleton segments indicate that stretching took place there. From these features it is concluded that the Wakarara Range as a whole was thrust southward in the later stages of its tectonic development (Fig. 9).

The different attitudes of the Waitotaran limestones on the eastern flank of the range are interpreted as follows (Fig. 8). As the Wakarara block started to rise, a longitudinal fault system developed, along which the block started to disintegrate into subsidiary segments, each segment carrying remnants of the Kaukau surface. Parts of the easternmost segment have tumbled eastward causing semi-overthrusting under the influence of gravity, this type of overthrusting is here termed a "gravity nappe". Evidence for various stages of this tumbling is to be seen along the limestone ridge from slightly overturned limestones in the Kereru ridge to completely overturned strata in the Eaton overthrust.

During the rise the block broke into two, the lines of fracture giving rise to Duff's Valley: the fault system developed is here called the Eaton fault system. The tumbling mentioned above in the Eaton overthrust was initiated along Duff's Valley, where the Eaton fault system crossed the easternmost longitudinal segment mentioned above (Fig. 9).

The Big Hill Block

The Big Hill block is situated between the Mohaka fault zone and the fault system in "The Orchard", the valley on the western side of the hill. Waitotaran and Nukumaruan strata are also folded around the southern end of the block. This block is also broken into two along the main branch of the Kaweka fault (Kingma, 1957a). The Kaukau surface on the northern side dips into the Kohurau depression; folding has not taken place around the northern end. Before the Ngaruroro River started to follow the Kaweka fault, it flowed consequently off the Kaukau surface, depositing gravels on the Longfellow area in the Kohurau district and on the northern segment of Big Hill. These gravels are here correlated with the Castlecliffian gravels elsewhere in

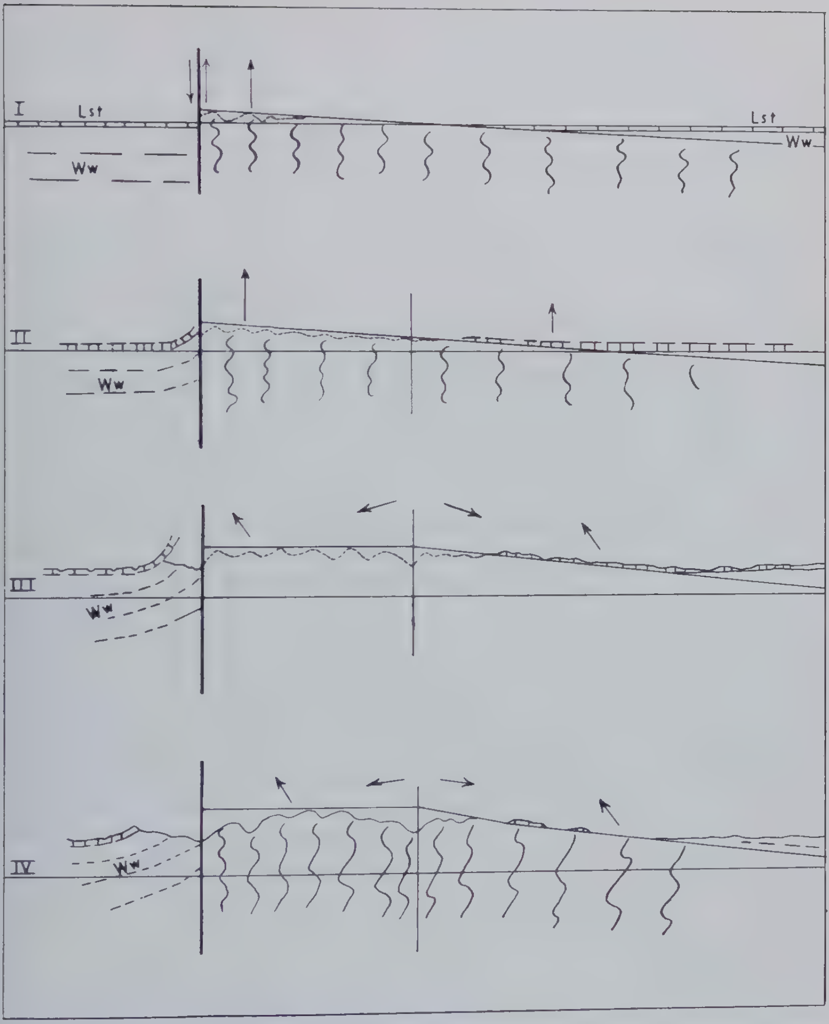

FIG. 9.—Sketched longitudinal sections through Wakarara Range showing history of block movements.

the district. The very similar features described from Big Hill and the Wakarara Range suggest that both blocks were thrust southward.

The Ruahine Block

All the greywackes west of the Ruahine fault system are here considered as part of the Ruahine Block. The Kaukau surface is well developed on the Ruahine Range (Fig. 10), and immediately attracts attention when the range is observed from a distance. The Ruahine fault is straight, and exceptionally well developed fault facets may be seen where it cuts the spurs leading into the Ohara depression.

The sag in the Ruahine-Rimutaka Horst west of Woodville, considered to be a fracture of the horst (Kingma, 1957c) provides a striking analogy with the Wakarara and Big Hill blocks.

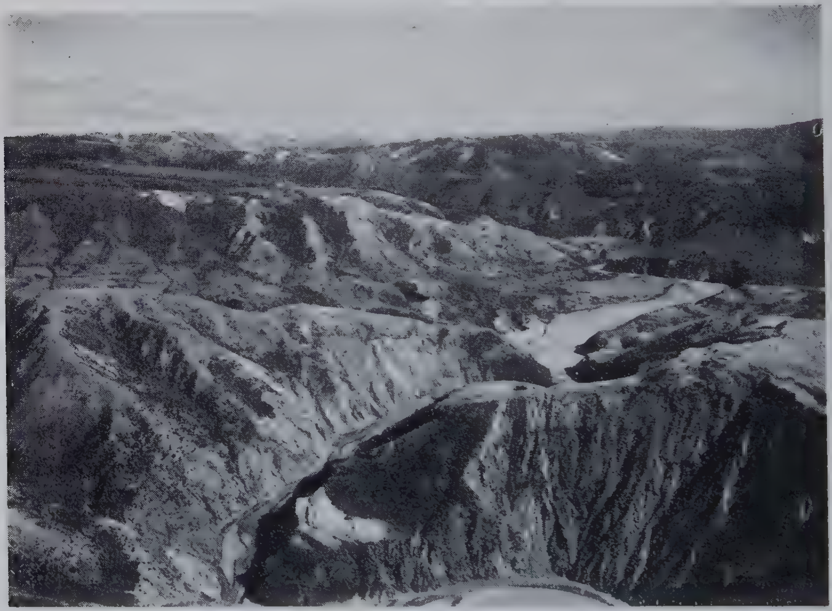

FIG. 10.—Ngaruroro River Gorge. Photograph taken across Big Hill gorge in westward direction. Note flat surface on Ruahine Range (top left corner), and Ruahine fault zone at foot of scarp below flat surface showing fault-facets. —*Photo, P. van Asch, Aerial Mapping, Hastings.*

The Ohara Graben.

The Ohara graben (Figs 2, 3, 4, 11), situated between the Ruahine and Mohaka fault systems, is approximately 12 miles long and 2 miles wide. Both fault systems exhibit dextral transcurrent movement in displacement of stream beds and of spurs (Kingma, 1957a). Towards Big Hill the graben is complicated by cross faulting before it dies out against the Big Hill block and into the Orchard fault angle depression. The sediments dip gently to the east (Fig. 6), but parallel and close to the Ruahine fault they are thrown into a gentle anticline, the western flank dipping at about 8° west. The Waitotaran limestones west of Sentry Box Hut are erosion remnants of what was a continuous sheet of limestone throughout the graben. At Ellis's hut the Ohara River captured some of the upper arms of the Makaroro system in that area.

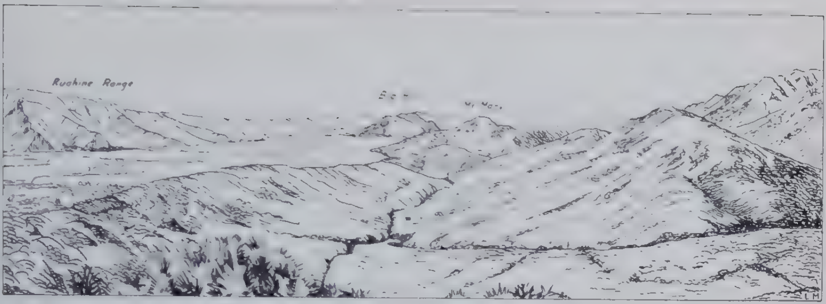

FIG. 11.—Sketch of the northern part of the Ohara depression.

Folded Tertiary Strata

As well as folded strata in the Ohara graben mentioned above, folded Tertiary strata occur in the southern part of the graben in the Yeoman syncline. The synclinal system is most clearly revealed in the Waitotaran strata (Fig. 5). Other folded strata appear in the Pebbly Hill syncline on the southern end of the range. The great thickness of Waitotaran strata here is well exposed in the Mangataura Stream and along the Mohaka fault.

Folded strata also occur in the Herricks anticline between Big Hill and the Ruahine Range. The axis plunges north-west at about 12° and is cut off by faulting (Fig. 2). The flanks dip 45° east and west. The presence of Nukumaruan marine strata above the Waitotaran limestone indicates that this area was accessible to the Nukumaruan sea. The folding is interpreted as being due to southward movement of the Big Hill block.

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EVIDENCE FOR A LOW SEA-LEVEL 9900 YEARS AGO

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(Received for publication, 29 August, 1957)

Summary

It is tentatively submitted that radiocarbon dating of *Podocarpus* wood from a well at Foxton suggests that sea-level may have risen about 150 ft during the last 9900 years, but there is no decisive evidence to indicate whether the land at the well site has been stable or tectonically elevated or depressed in recent times.

Introduction

In most parts of New Zealand, attempts to decipher the record of Pleistocene eustatic changes of sea-level are hampered by ignorance of precise dates of late tectonic movements. Prior to the advent of radiocarbon dating, the New Zealand geologist, faced with the task of interpreting rise and fall of sea-level and elevation and depression of the land, did not have a single reliable "time-plane" to serve as a reference datum, so that detailed correlation of late geological events in one district with those of adjacent districts has been highly speculative. It now seems probable that systematic work with radiocarbon dating will eventually enable separation of the effects of eustatic movements of sea-level from those of tectonic movements.

^{14}C Sample from Foxton

Locality

In November 1953, Mr Victor Richardson drilled a well to increase the water supply for the Borough Council at Foxton, 62 miles north-north-east of Wellington. The well is sited 15 chains north-west of the Foxton Water Tower, on the east (right) bank of the Manawatu River, 3·5 miles from its mouth; grid reference: Provisional One Mile Map Series, Tangimoana Sheet N 148/796206.

Bore Log

The ground surface at the top of the well is 5 ft above mean sea-level. In the following bore log, the figure in brackets represents the thickness, in feet, of individual beds.

N.Z. J. Geol. Geophys. 1 : 92-4.

Feet	Thickness (feet)	
0 to 5	(5)	Silt
5 to 25	(20)	Sandy gravel
25 to 41	(16)	Coarse sand and gravel with shells and shell fragments
41 to 71	(30)	Coarse sand
71 to 80	(9)	Clay and sand
80 to 109	(29)	Sand
109 to 110	(1)	Sand with shells and shell fragments
110 to 155	(45)	Clay and sand
155 to 157	(2)	Log of wood (^{14}C age: 9900 ± 150 years)
157 to 182	(25)	Clay and sand
182 to 218	(36)	Gravel; pebbles well rounded, mostly less than 2 inches in diameter

Mr Richardson noted that all sediments in the well were very soft and not rusty (unoxidized).

Wood Sample

The top of the dated log of wood, 2 ft in diameter, was encountered 150 ft below present mean sea-level. Mr H. R. Orman, of the New Zealand Forest Service, identified the wood as *Podocarpus* sp. (probably *P. totara*). The age of the wood (Grid, ref. N 148/796206, N.Z. Fossil No. N 148/503) was determined at the Isotope Laboratory, Nuclear Sciences Division, D.S.I.R., to be 9900 ± 150 years.

Comments

It is tentatively assumed that the dated log was drift wood probably stranded in the intertidal zone and later buried beneath estuarine and/or shallow water marine sediments when sea-level rose as an accompaniment of the melting of the last ice sheets. If the land has been stable at the well site for the last 9900 years, it would appear that sea-level has risen 150 ft during this period; but this simple assumption is unsupported by any evidence. At present along the Manawatu coast the land is gaining at the expense of the sea due to both progradation and general emergence brought about by tectonic uplift. Terraces of the lower reaches of the Manawatu River near Palmerston North suggest that the later geological history has been characterized by general uplift. If there has been recent uplift at the well site, it would appear that sea-level has risen more than 150 ft in the last 9900 years. It must be emphasized, however, that there is no decisive evidence to indicate whether the land under discussion has been stable or tectonically elevated or depressed in recent time. Until further information becomes available, it may be tentatively submitted that study of the dated wood from the Foxton well suggests that sea-level may have risen about 150 ft during the last 9900 years.

In an overseas radiocarbon study of postglacial rise of sea-level, Shepard and Suess (1956, Fig. 1, p. 1083) show "radiocarbon ages relative to depths below sea-level" of 34 "samples of wood and shell . . . believed to have been deposited essentially at sea-level." These authors note that in their figure "no correction has been made for compaction or subsidence from other causes," and also point out "that many more measurements from a variety of locations must be made before it will be possible to distinguish conclusively between eustatism, tectonic movements, and compaction." In their diagram, Shepard and Suess show several samples that may be compared with the Foxton sample, i.e., 3 samples about 9000 years old from about 70 ft below sea-level, 1 sample about 10,000 years old from about 120 ft to 130 ft below sea-level, and 1 sample about 11,000 years old from about 170 ft below sea-level. Brannon *et al.* (1957, pp. 921–2) discuss samples from southern Louisiana and the adjacent continental shelf that suggest that sea-level stood about 75 ft lower than at present 8800 years ago, about 110 ft lower than at present 8950 years ago, about 150 ft lower than at present 10,700 years ago, and about 165 ft lower than at present 11,200 years ago.

From Australia, Gill (1956, p. 136) has reported that "there is evidence in Melbourne of a lower sea-level which ^{14}C analysis shows to be synchronous with the Mankato glaciation. About 9000 years ago, the sea was at least 73 ft lower than now, and the climate was colder and wetter. The channels cut by the rivers as a result of the low sea-level reached at least 100 ft below the present level of the sea and may be as much as 150 ft."

ACKNOWLEDGEMENT

The writer is indebted to Mr Victor Richardson, of Richardson & Sons, well-drillers, Palmerston North, for collecting the wood sample and providing the bore log.

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PLEISTOCENE SHORELINES AT PORIRUA HARBOUR, NEAR WELLINGTON, NEW ZEALAND

By M. L. LEAMY, Soil Bureau, Department of Scientific and Industrial Research.

(Received for publication, 20 September 1957)

Summary

This paper deals only with ancient shoreline features found near the northern and eastern shorelines of the Pauatahanui Inlet of Porirua Harbour. Correspondence of the heights of these features with heights of Pleistocene shorelines overseas is remarkably close. Although Porirua Harbour lies in a tectonically unstable environment, a hypothesis advanced by Cotton (1952) suggests that the Harbour itself may have largely escaped the effects of recent differential earth movements. Pleistocene shorelines could well be preserved in such a locality, and terraces are correlated by height with the (post-glacial) thermal maximum, Late Monastirian, Main Monastirian, Tyrrhenian, Milazzian, and Sicilian shorelines of other regions.

INTRODUCTION

Pleistocene shorelines, formed when sea level stood higher than at present, have been identified in many parts of the world. Zeuner (1945, p. 246) quoted a series of five former sea levels originally identified and named in the Mediterranean area and subsequently correlated with other shorelines of similar heights in North France, Jersey, South England, South Africa, Sunda Archipelago, South Australia, and North America. In some instances correlations were made despite considerable differences in the observed shoreline heights (e.g., 22 metres between the Sicilian shorelines of Algiers and North America, Zeuner, 1945, p. 246).

The high sea levels represented were attributed to Interglacial phases of the Pleistocene Glaciation.

PREVIOUS WORK IN NEW ZEALAND

In 1924 Henderson collected and reviewed evidence for post-Tertiary sea-level fluctuations in New Zealand. Gage (1953) produced a comprehensive review of information collected between 1924 and 1950, and issued a warning (*op. cit.* p. 32) that, because of the inexactitude and ambiguity of much of the existing data, "Anyone wishing to pursue further the study of old strand-lines in New Zealand will have to consider the abvisability of making an entirely fresh start. . . ."

N.Z. J. Geol. Geophys. 1 : 95-102.

Gage also emphasised the current view that because New Zealand, with the possible exception of North Auckland and East Otago, has been widely affected by late differential earth movements, little could be contributed from this country to a world-wide strand-line study. Fleming (1951) was also well aware of the complications introduced by differential earth movements which have continued into recent times, but considered that sea-level changes could be used to establish local chronologies, and that correlation with other regions might be attempted.

The work of Brothers (1954) on the relatively stable North Auckland Peninsula demonstrated that in this region at least, feasible correlations with Pleistocene shorelines overseas can be made.

Stevens (1957) indicated possible eustatic levels in the Hutt Valley and at Port Nicholson and mentioned probable eustatic benches in the Porirua Harbour District.

Te Punga (1954) drew attention to these Porirua Harbour benches and particularly to the Walker Trig bench which he tentatively correlated with the Tyrrhenian shorelines. He also suggested the correlation of lower benches with Late Monastirian and (post-glacial) thermal maximum shorelines and concluded (*op. cit.* p. 172) that "If the Walker Trig bench and lower marine terraces are indeed features directly related to changing sea levels, correlation with northern hemisphere equivalents seems assured."

In the present paper an attempt is made at such a correlation for although Porirua Harbour lies in a tectonically unstable environment, a hypothesis advanced by Cotton (1952) and outlined below suggests that the harbour itself may have largely escaped the effects of recent differential earth movements.

DESCRIPTION

Porirua Harbour is an embayment of the western Wellington coast about 17 miles north of Wellington city (Fig. 1). The harbour consists of two inlets almost at right angles to each other, the Pauatahanui Inlet (Fig. 2) lying N.W. to S.E. and the Porirua Inlet to the south extending in a N.E. to S.W. direction. This paper deals only with features found near the northern and eastern shorelines of the Pauatahanui Inlet.

Adkin (1921) discussed the shoreline and other physiographic features of Porirua Harbour and concluded (*op. cit.* p. 156) that it ". . . is the result of the partial drowning of a normal valley system modified since the submergence by the several phases of marine abrasion and deposition."

In order to explain the various stages of emergence and submergence observed on the Wellington coast from Port Nicholson to Porirua Harbour, Cotton (1952) proposed a hypothesis of transverse deformation. He considered that this deformation had taken place

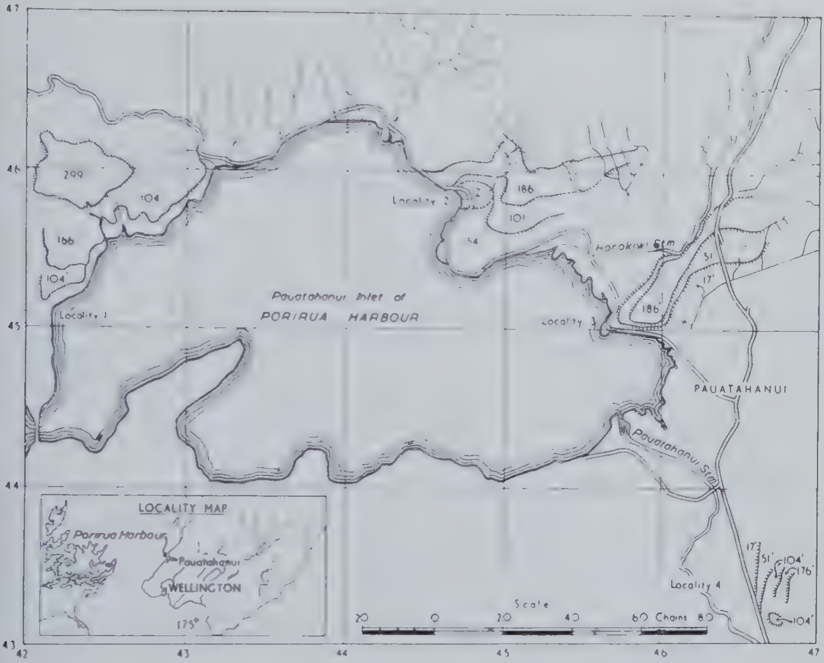

FIG. 1.—Sketch map of Pleistocene shorelines, Porirua Harbour, and locality map.

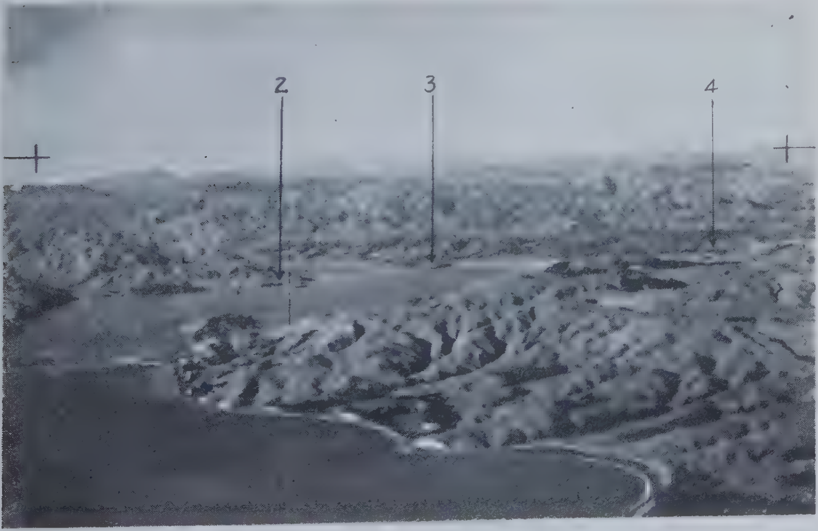

FIG. 2.—Aerial view of Pauatahanui Inlet, Porirua Harbour, showing localities 2, 3, and 4. Porirua Inlet is in the foreground. (Photo D. W. McKenzie.)

in geologically recent times and that it was responsible for the presumably contemporaneous elevation and depression of neighbouring parts of the same coast.

Referring to Porirua Harbour Cotton stated (*op. cit.* p. 61) that, "In the embayed part of the western coast at Porirua Harbour there is little or nothing to suggest recent tectonic submergence. The drowning is not so great that it cannot be accounted for by eustatic submergence. It appears that this area escaped the latest diastrophism. . . ."

Features due to high stands of sea-level of comparatively recent age could well be preserved in such a region.

But it must be noted that the Harbour has not been entirely unaffected by earth movements in recent times. Adkin (1921) quoted evidence showing that the uplift due to the 1855 earthquake produced a raised shore platform which now lies about 3 ft above high water level. This uplift of 3 ft was uniform at least throughout the Pauatahanui Inlet (Adkin, 1921, p. 149) and is small enough to be of little significance in a broad correlation of terraces with eustatic sea-level fluctuations in the Pleistocene.

Topographic features which are considered to represent ancient shorelines were observed at four localities within a half-mile wide belt around the northern and eastern shorelines of the Pauatahanui Inlet These features vary from well-preserved terraces (Fig. 3) with treads up to 20 chains wide to low flat-topped hills and ill-defined steps in

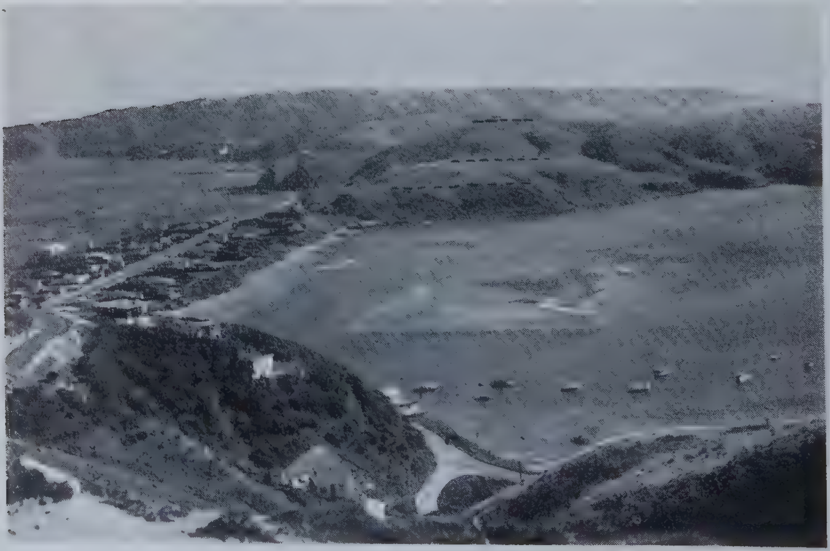

FIG. 3.—Looking north across Pauatahanui Inlet at the well-defined benches at Locality 1. (Photo M. D. King.)

total constitutents ratios without adversely affecting the gelling pro-
the topography. Heights were measured with an aneroid barometer, accurate to 5 ft, and recordings were taken where possible at the inside or landward margin of the terraces.

Table 1 shows the terrace heights (corrected to mean sea-level—the present mean tidal range is 7·0 ft), heights of overseas terraces attributed to glacio-eustatic fluctuations (Zeuner, 1945, p. 246), and the correlations. At no single locality around Porirua Harbour was the full sequence of levels quoted by Zeuner found but, considering the area as a whole, benches at six different heights were identified. The greatest distance between the localities at which measurements were made was 3 miles. The figures are the average of two readings taken at different sites on each bench.

TABLE 1.—Correlation by height of terraces at Porirua Harbour with glacio-eustatic terraces in other parts of the world.

Locality and grid ref.	Terrace heights (ft)	Correlation	Heights of overseas terraces converted from metres to feet	
			Average (ft)	Variation (ft)
1 N. 160 423/450-460 (Fig. 3)	104	Tyrrhenian	105	88·5 to 111·5
	166	Milazzian	197	147·5 to 246
	299*	Sicilian	328	266 to 338
2 N. 160 449/455-460 (Fig. 2)	12	(post glacial) thermal maximum		
	54	Main Monastirian	59	49 to 65·5
	101	Tyrrhenian	105	88·5 to 111·5
	186†	Milazzian	197	147·5 to 246
3 N. 160 464/455 (Figs 2 & 4)	17	Late Monastirian	24·5	16·5 to 26
	51	Main Monastirian	59	49 to 65·5
	186†	Milazzian	197	147·5 to 246
4 N. 160 468/431 (Fig. 2)	17	Late Monastirian	24·5	16·5 to 26
	51	Main Monastirian	59	49 to 65·5
	104	Tyrrhenian	105	88·5 to 111·5
	176	Milazzian	197	147·5 to 246

*Indicates a flat-topped hill where the landward bench margin has presumably been removed by erosion.
†1 reading only taken here.

King (1930) warned of the danger of confusing marine terraces and alluvial plains when determining the origin of bench remnants. He suggested certain criteria (p. 521) which he used to distinguish more extensive features than are discussed in this paper. The vestigial nature

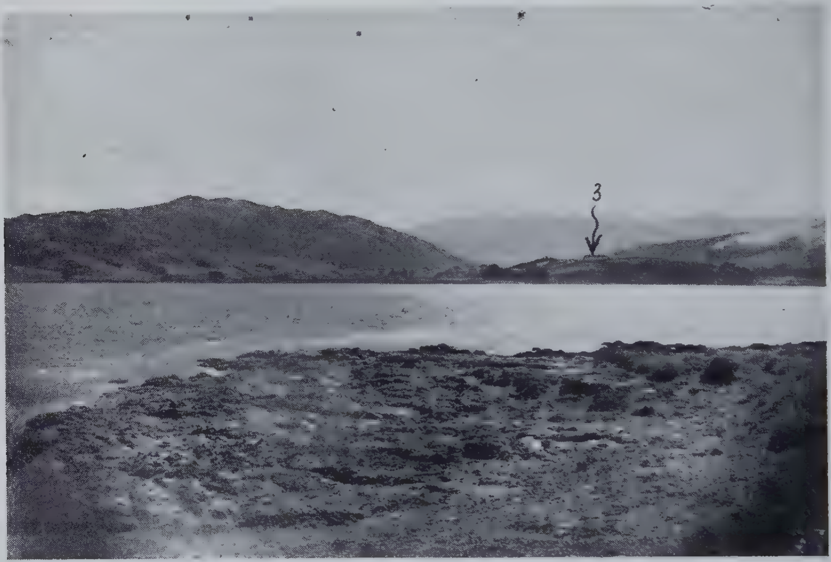

FIG. 4.—Looking north across Pauatahanui Inlet at the mouth of the Horokiwi Valley with Locality 3 to the east. (Photo M. D. King.)

of the bench remnants along the northern and eastern shores of Pauatahanui Inlet makes a confident prediction of their origin extremely difficult. Although measurements were made on the assumption that the benches are marine, the possibility that they are alluvial plain remnants cannot be completely ignored. As King (1930, p. 521) pointed out, previous sea-levels are recorded at the rear edge of a marine terrace, but at the seaward margin of an alluvial plain remnant. At Porirua Harbour, with the exception of the top bench at Locality 3 (Fig. 4), the remnants are of such limited areal extent that the difference between a reading taken at the seaward edge and one taken at the rear edge would hardly have been great enough to have been recorded on the instrument used. The top bench at Locality 3 extends for some 40 chains inland, and because of its position in the landscape, is of doubtful origin. If it is an alluvial plain remnant, the height of the previous sea-level would be of the order of 10 ft lower than that shown in Table 1.

A brief description of the underlying deposits at the four localities is given in Table 2.

DISCUSSION

Correspondence of terrace heights at Porirua Harbour with heights of Pleistocene shorelines overseas is remarkably close. This evidence suggests that the Porirua Harbour features are Pleistocene shorelines

TABLE 2.

Locality	Position in landscape	Nature of underlying deposits	Origin of terrace
1	On a promontory at the mouth of Pauatahanui Inlet	299 ft: gravels of Judgeford Formation (Leamy, 1955, p. 5) 166 ft: clay and silty clays of the Plimmerton Formation (Leamy, 1955, p. 7) with pockets of rubified clay on greywacke (in some places rubified). 104 ft: Plimmerton silty clays over Judgeford gravels.	probably marine
2	On the promontory immediately west of the flood-plain of the Horokiwi Stream	186 ft: greywacke. 101 ft: greywacke. 54 ft: Medium and coarse greywacke gravels probably of the Judgeford Formation. 12 ft: Fine greywacke gravels (beach deposits?)	probably marine
3	At the south-eastern boundary of the flood plain of the Horokiwi Stream	186 ft: rubified ash shower material over gravels of the Judgeford Formation. 51 ft: silts and greywacke gravels probably of the Judgeford Formation. 17 ft: Fine and medium greywacke gravels.	probably alluvial
4	On the ridge to the east of the valley of the Pauatahanui Stream	176 ft: greywacke. 104 ft: greywacke. 51 ft: greywacke gravels of the Judgeford Formation. 17 ft: greywacke gravels.	probably marine

and that the relative time scale erected on the evidence of the overseas shorelines may be applicable in this district.

According to Zeuner (1945, p. 249 to 251) the relative ages of the overseas high sea levels in the Pleistocene are as follows:

Sicilian: Immediately precedes the Early Glaciation.

Milazzian: Antepenultimate Interglacial.

Tyrrhenian: Great or Penultimate Interglacial.

Main Monastirian } Last Interglacial.
Late Monastirian }

If this correlation is valid it should provide datum lines for establishing, in the immediate area of Porirua Harbour at least, the relative age of some of the superficial covering deposits such as certain solifluxion deposits, windblown sands, fossil soils, ash showers, and rubified deposits. If the terrace heights recorded here can be matched with those of terraces of the south shore of the Pauatahanui Inlet and around the Porirua Inlet the hypothesis presented above will be strengthened considerably. It is highly desirable that future research in this area should be based on precise levelling.

ACKNOWLEDGEMENTS

This paper formed part of a thesis presented for M.Sc.

The writer is indebted to the Professor and staff of the Geology Department of Victoria University of Wellington, and particularly to Dr M. T. Te Punga, for criticism and advice.

Messrs J. D. Raeside and J. D. McCraw, provided constructive criticism.

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LATE QUATERNARY DEPOSITS OF THE CHRISTCHURCH METROPOLITAN AREA

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(*Received for publication, 29 August 1957*)

Summary

Deep wells sunk for artesian water beneath Christchurch penetrate three formations. The youngest, the Christchurch Formation, consists of marine, estuarine, and fluviatile deposits of which at least the upper part was formed during the post-glacial rise of sea-level. It extends down to more than 200 ft below present sea-level, and radiocarbon dates record part of the rise of sea-level, from — 73 ft 9400 years ago (S83/501) to — 12 ft 6100 years ago (S84/523). Other dates, together with topographic and soil evidence, are interpreted as indicating the subsequent period of development by the Waimakariri River of a fan of gravel over the Christchurch area, probably completed about 2,000 years ago when sea-level was a little higher than at present. The aggradation surface of this fan is termed the Yaldhurst Surface.

The Riccarton Gravel, on whose eroded surface the Christchurch Formation lies, is thought to be the sub-surface representative of the gravel that forms an earlier fan, whose surface—the Halkett Surface—also has characteristic soils. This fan is believed to have developed as the result of aggradation by outwash streams during the last but one major advance of "Last" Glaciation age.

Glacial outwash gravels of a still earlier "Last" Glaciation advance form an older fan whose surface—the Darfield Surface—is also recognized from topographic and soil evidence. No sub-surface representative of these gravels is recognized beneath Christchurch.

The Bromley Formation, estuarine and marine gravel, sand, silt, and peat, extends down to several hundred feet below the Riccarton Gravel beneath most of Christchurch; it is thought to be of "Last" Interglacial age. In the western part of the Christchurch area, thick gravel beneath the Riccarton Gravel may perhaps be of "Penultimate" Glaciation age.

INTRODUCTION

From the foothills of the Southern Alps to the sea or to the western margin of Banks Peninsula, the Canterbury Plains appear superficially to have a uniform surface, broken only where the Waimakariri and other rivers are entrenched beneath it. Both north and south of Banks Peninsula, the surface grades down to sea-level, but at the foot of the Peninsula it is about 50 ft above sea-level at Halswell on the watershed between the Heathcote River flowing to the north-east and the Halswell River flowing to the south (Fig. 1).

The superficial uniformity of the surface between the major rivers is deceptive. A hint of this is given by Haast (1864, p. 48, and map), and Speight (1928, p. 212) noted "the Plains . . . have the character of a double fan . . . [the younger] at a gentler grade, the two intersecting in the vicinity of Courtenay." He attributed this to tilting

N.Z. J. Geol. Geophys. 1 : 103-22.

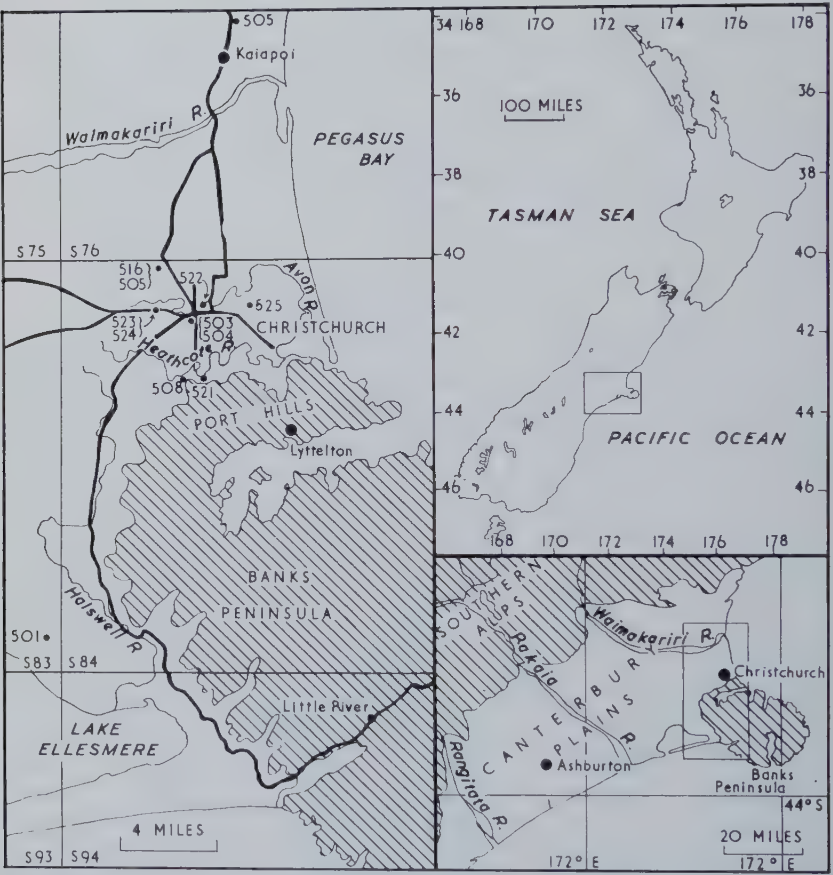

FIG. 1.—Locality maps. The left-hand map shows positions of samples for which radiocarbon ages are available. The bottom right-hand map shows the extent of the Canterbury Plains formed by glacial outwash gravels and post-glacial gravels; coalescing fans from the three major rivers shown built up the plains during the "Last" Glaciation.

of the older fan, prior to the formation of the second. Speight suggested that the main (older) surface of the plains was formed by glacial outwash, and that the outwash gravels become finer eastwards, being deposited under predominantly marine conditions in the Christchurch area. To account for peats and shells several hundreds of feet below the surface near the coast, he postulated progressive sinking of the coastal area relative to the inland margins of the plains. These conclusions have been accepted by recent authors—for example, Alley (1955)—but Collins (1949, p. 252) suggested "oscillations of sea-level during an extended period of submergence" to account for the finer coastal beds.

For the Christchurch metropolitan area, stratigraphic information of varying degrees of detail and reliability is provided by a great number of wells. Innumerable water wells have been sunk to tap artesian aquifers at various depths down to 600 ft, and rapid vertical and horizontal changes of lithology in gravels, sand, silt, and peat have made extensive testing essential where large structures are to be built.

The stratigraphic information is supplemented by interpretation of surface contours in terms of a series of aggradational surfaces, which can also be recognized through differences between soil types. A series of radiocarbon dates adds precision to some details of interpretation.

STRATIGRAPHY OF THE CHRISTCHURCH FORMATION

The four typical well logs illustrated in Fig. 2, with locations shown on Fig. 5, show the great variations in detail found across the Christchurch area. In interpreting the several hundreds of logs of wells whose locations are accurately known to the New Zealand Geological Survey, Christchurch, the variations of colour have, in the first instance, proved to be of greatest value. Two colours predominate in drillers' descriptions—brown and blue. The former is taken to indicate oxidized iron, the latter reduced iron; differences in intensity of brownness, which might indicate degrees of oxidation, are not recorded, but the oxidation appears to be largely superficial on the pebbles. The upper beds in wells 236, 120A, and 122 (the numbering is that adopted by the New Zealand Geological Survey, whereby all wells within each of the N.Z.M.S. 1 sheet areas are numbered serially as information is received), apart from those within a few feet of the surface, are described as blue; they are underlain by brown gravel, which passes down to finer beds, still mostly brown in colour but containing occasional layers described as blue. In unbroken sequences of gravels, sands, etc., oxidation is found near the surface, and unoxidized beds below. Inversion of this usual direction of colour change is common in many outcrops of gravels elsewhere in Canterbury—for example, in high river-terrace faces—and is usually taken to indicate a significant break where the reversal takes place, the lower beds having been subjected to weathering during some period prior to the deposition of the higher beds. The oxidation of several hundreds of feet of gravels, as in Well S84/122, is not exceptional in New Zealand. The blue beds within the brown require explanation, and it is commonly found—as in Well S84/120A— that clays and/or peats are included in that part of the section described as blue; reduction of iron in the presence of organic matter appears to account for the colour change.

Thus the important stratigraphic horizon is that of the top of the highest brown bed, unless this is close to the surface, since oxidation takes place between the surface and the water table. In general, the depth to the water table is less than 5 ft throughout the Christchurch area, but increases progressively westwards from Riccarton. Figure 3 shows contours representing the top of the highest brown-coloured bed beneath Christchurch—that is, the base of the overlying formation

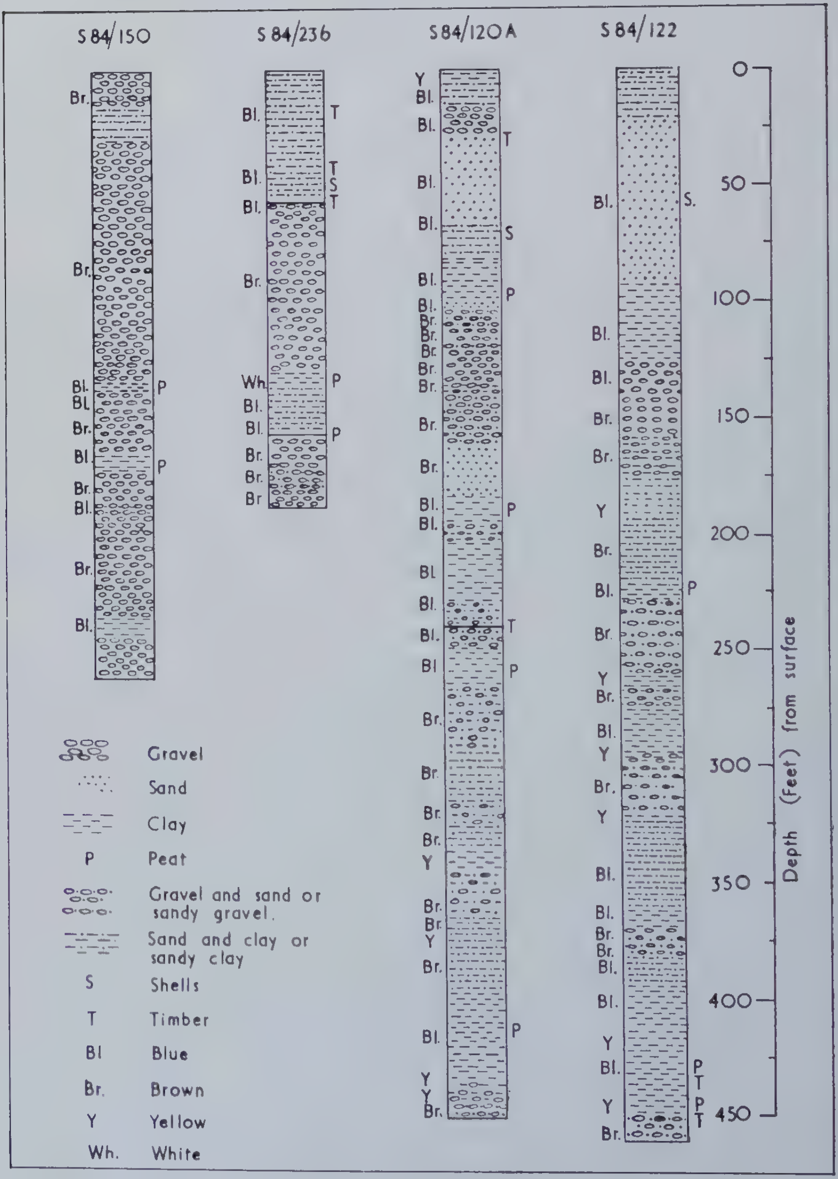

FIG. 2.—Typical well logs from Christchurch Metropolitan area. For location, see Fig. 5.

which is here termed the Christchurch Formation. As the sequences through the Christchurch Formation differ greatly from place to place, the sequences from 0 to 102 ft in Well S84/120A, 0 to 140 ft in Well S84/122, and 0 to 60 ft in Well S84/236 are designated type sections. In preparing Fig. 3, all available well logs for which colour descriptions are given were first used, and then it became clear that over the whole area, apart from locally in the extreme east, the highest brown bed is a thick gravel, almost everywhere thicker than gravel beds within the Christchurch Formation. This feature made it possible to use many more logs in preparing Fig. 3, and details of contours were refined without changing the general pattern. The pattern is one of stream erosion, with a pronounced ridge separating a steep-sided valley along the northern foot of the hills from a second valley three miles to the north. There is little evidence for the + 25 ft and + 50 ft contours, but the base of the Christchurch Formation appears to approach the present-day surface at about Upper Riccarton.

Shells, usually in sand or sandy clay, are common within the Christchurch Formation, and it is certain that they are far more common than reported in drillers' logs. Peats, usually with tree remains and interbedded with clay, are found predominantly near the base and the top. Gravel is found at the base in the east, at levels more than 100 ft below sea-level; through the central area a north-north-east trending belt contains gravel at intermediate levels, principally between a few feet above sea-level and 30 ft below; gravels more than 10 ft above sea-level are almost confined to the north-west and south-west. Three cross-sections (Fig. 4) illustrate the variations of the Metropolitan area.

In cross-section B–B′, the intermediate level of gravel is well shown, and sands with shells are recorded both in the extreme east (Well S84/122) and in the west (Well S84/236*), at similar levels. These gravels are interpreted as beach gravels, deposited contemporaneously with off-shore, shell-bearing sands to the east and estuarine shell-bearing silts and sands to the west. During excavations for the Christchurch Drainage Board's Northern Relief Sewer at its crossing of the Avon River at Morris Street, blue-grey gravel with a dominant proportion of flattened pebbles was exposed at river level, the top of the gravel being about 4 ft above mean sea-level. Although flattening may not be an infallible criterion of beach deposition, the gravel contrasts markedly with the fluviatile gravel of the plains and in the Waimakariri River bed, and gives some support to the suggested beach origin of these intermediate-level gravels.

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*Of the three logs of wells at the Clarence Road pumping station of the Riccarton Borough Council, within 30 ft of one another, two record gravels (one blue gravel and the other brown gravel) between about 55 and 135 ft, whereas the other records only blue clay, sand, and peat through this part of the sequence. The variations appear excessive, even for the Christchurch region. The record of blue gravel from 58 to 60 ft with brown gravel from 60 ft to 132 ft at another Riccarton Borough Council well little more than a quarter of a mile away at Mandeville Road, is similar to that expected in geological interpretation.

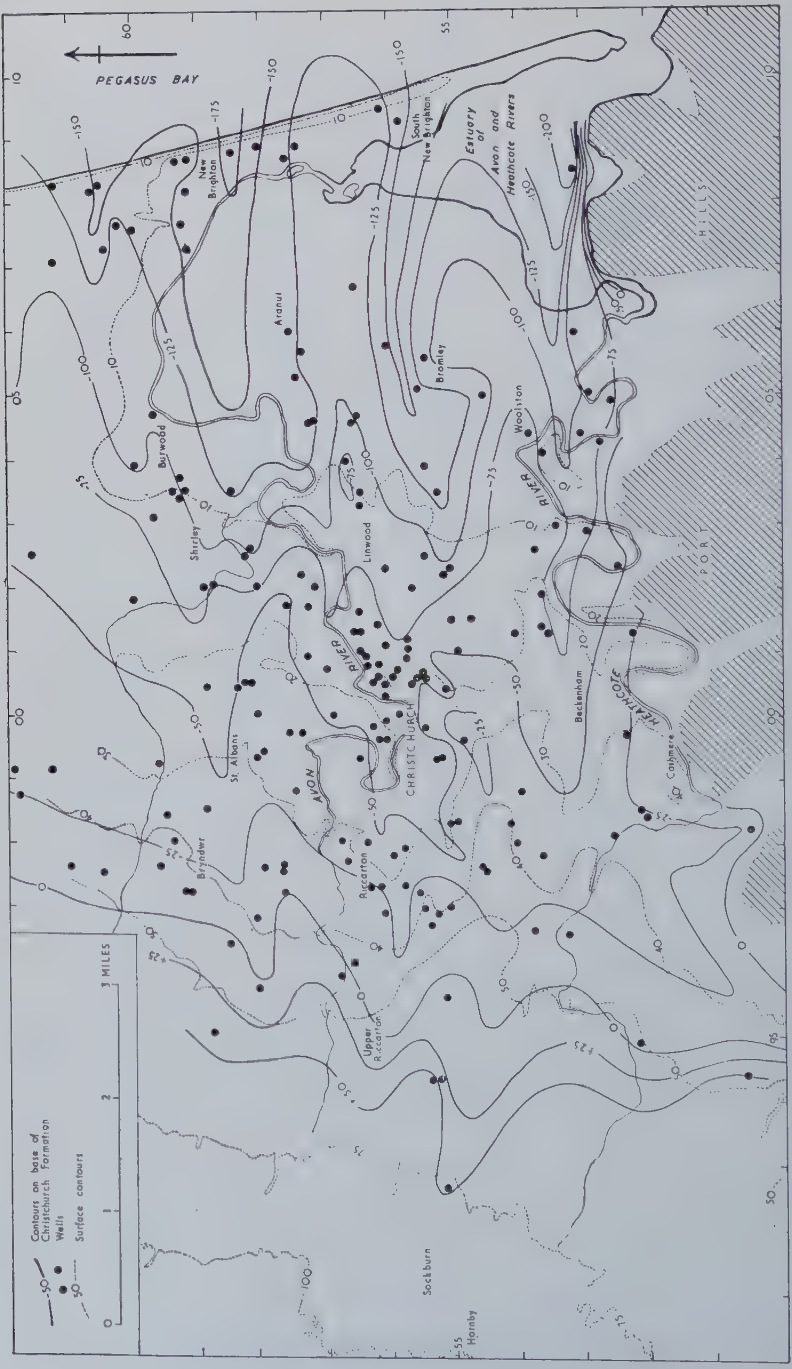

FIG. 3.—Contours of base of Christchurch Formation, Christchurch Metropolitan area.

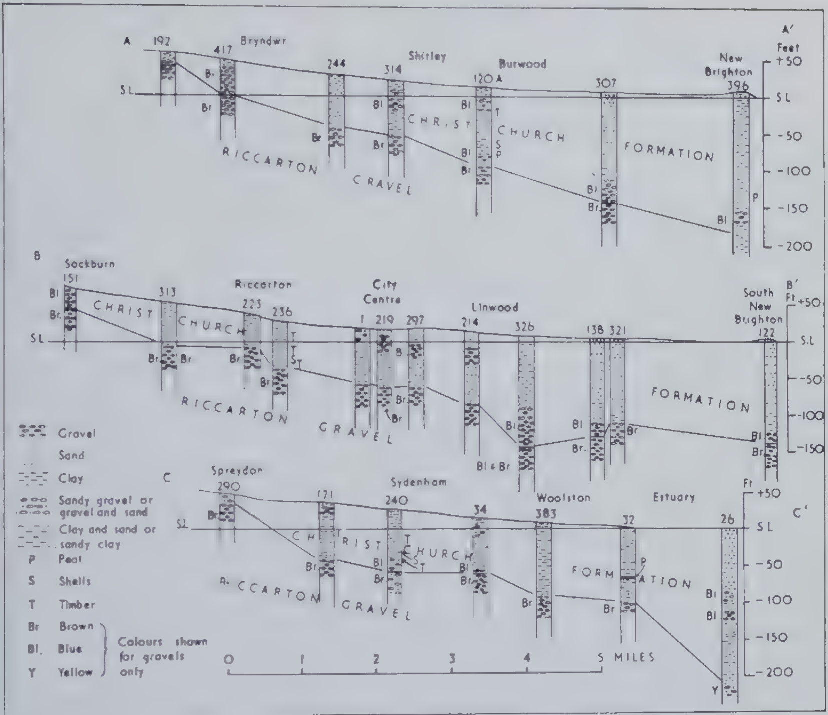

FIG. 4.—Well logs illustrating variations in the Christchurch Formation. For section lines, see Fig. 5.

The lower-level gravels to the east, basal beds of the Christchurch Formation, are less certainly marine, and may well be fluviatile gravels deposited with rising sea-level before the sea actually reached the area. Between these basal gravels and the shell-bearing beds are clays and peats, probably estuarine.

The north-westerly and south-westerly gravels, above sea-level, are likely to be fluviatile deposits of the Waimakariri River when it built a fan over the Christchurch area (see pp. 114-5). Although the Christchurch Formation cannot be detected in wells west of Upper Riccarton, it seems probable, judging by contours, that it decreases rapidly in thickness to the west, forming only a thin veneer over older beds from Hornby westwards (see Fig. 6 showing relation of aggradational surface of Christchurch Formation to those of older surfaces).

SURFACE TOPOGRAPHY AND SOILS

Figure 5 shows surface contours for part of the Canterbury Plains, from the lower Waimakariri gorge to the sea, including the Christchurch metropolitan area. The contours are taken from the Lands and Survey 1-mile maps (N.Z.M.S. 1) with contours at 100-ft intervals for the western part of the area, and from the 1:25,000 maps (N.Z.M.S. 2) with 25-ft contours for the eastern part. The general contour pattern is that of a fan below which the river is entrenched in the north-west and which is complicated by minor dissection in the south-west. The detail of the contour pattern reveals complexity in fan development and small kinks in the contours become significant. In the west, any particular contour, when traced towards the river, kinks upstream owing to terracing of the main surface of the Plains. In the centre, when, for example, the 300 ft contour is traced towards the river, it kinks downstream, indicating a slight rise in the surface of the plains. Upstream terrace levels can be correlated with downstream surfaces slightly higher than the main plains' level, the pattern being due to the formation of lower-gradient fans below the level of main plains' surface at the gorge and above it farther downstream. Two fans younger than the fan that forms the main plains' surface are recognizable by surface contours, and confirmation is given by the soil evidence. Recent maps* published by the Soil Bureau, Department of Scientific and Industrial Research, in 1954 show many different soil types whose distinctive characters allow them to be grouped according to age.

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*The soil maps are those of the "Soils of the Downs and Plains of Canterbury and North Otago, New Zealand"; the accompanying bulletin is in preparation. Mr W. T. Ward, of the Soil Bureau, Christchurch, has kindly provided the following note concerning the age groupings of soils, which were first interpreted by pedologists as indicating threefold fan development during the soil survey of the plains in 1946–48.

"The soils of the Canterbury Plains fall naturally in three major groups according to age, a factor which is reflected in the degree of profile development. The first of these groups includes the soils of the coast and 'lowlands fringe,' and for convenience may be termed the 'Waimakariri group,' the name being that of a widespread and typical soil series contained within it. Soils of Waimakariri group have no clearly defined horizons, their topsoils resting on raw and in most places unweathered sediments. Chemical analyses show that they are slightly acid (pH 5·1 to 7·1; average 6·0) and are very weakly leached (average % base saturation —71). They have a high content of citric acid-soluble phosphate (average 0·041%).

"The second, or 'Paparua group,' includes the soils of the 'fan margins and low terraces.' These soils have clearly differentiated topsoil and subsoil horizons and are moderately acid (pH 4·8 to 6·6; average 5·6), weakly-to-moderately leached (average %BS — 58), and have a moderate content of phosphate (average 0·025%). Certain soils of the 'fans and high terraces' namely, Kowai, Highbank, Gorge, Barr Hill, and Hatfield series, have profiles and properties similar to the soils of Paparua group, but they are of little use as a key to the history of terrace development for, though they are widespread on the fans and high terraces, they bear no clear relation to topography. This is a consequence of the peculiar mode of deposition of their parent material—loess, still actively accumulating in many places—which lies as a blanket over terraces, clearly of different ages, adjacent to the major rivers.

"The third, or 'Lismore group,' includes those soils of the 'fans and high terraces' that are not formed on deposits of loess. These soils have the most mature profiles for soils of the plains. They have well developed horizons and are moderately-to-strongly acid (pH 4·7 to 5·9; average 5·2), strongly leached (average %BS ≎ 27), and have a moderate-to-low content of phosphate (average 0·018%)."

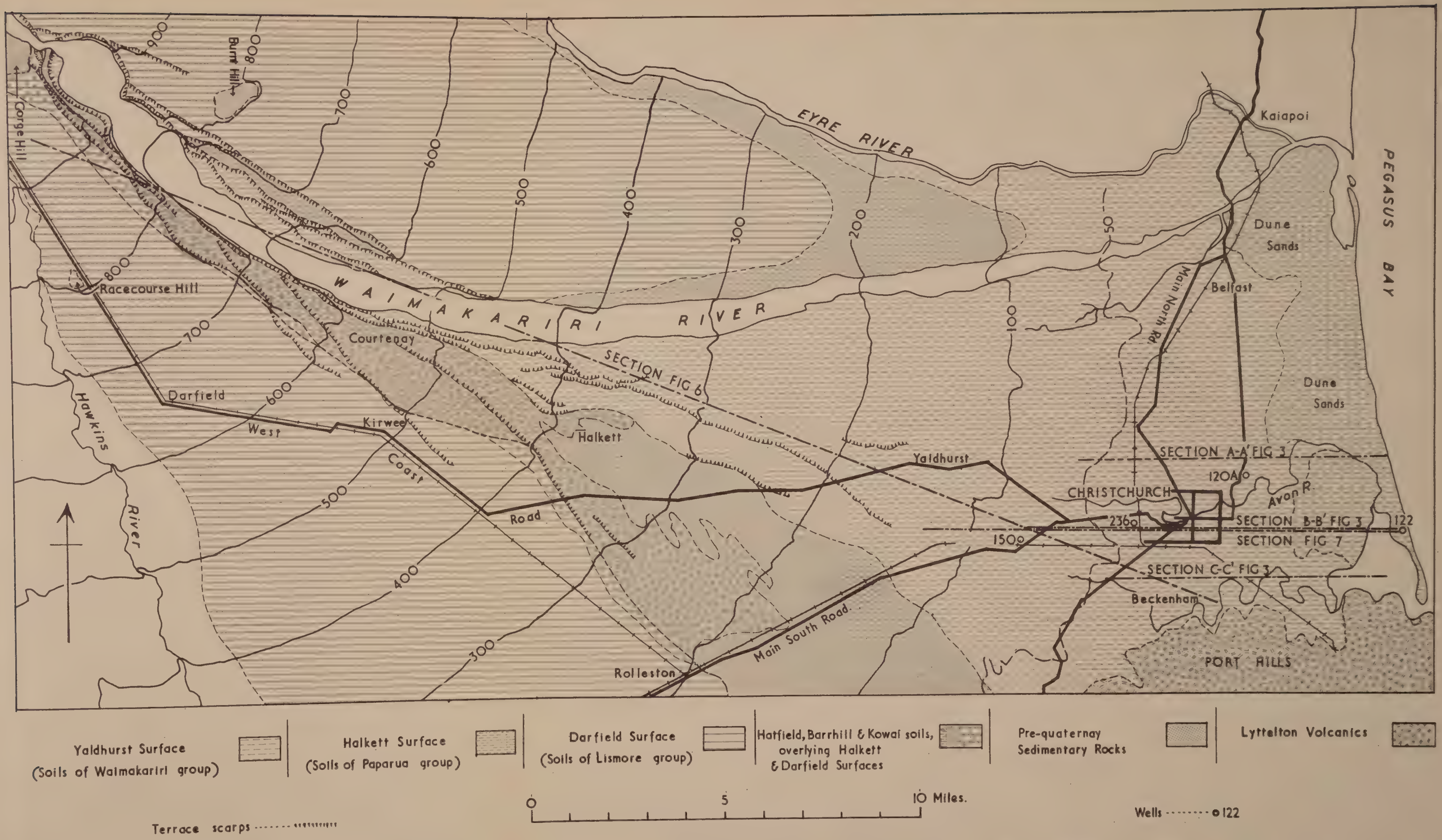

Fig. 5.—Soils and topography of the Christchurch area. (Soil boundaries from Sheets 1 and 2. "Soils of the Downs and Plains, Canterbury, and North Otago," maps published by the Soil Bureau, D.S.I.R., 1954.)

For Fig. 3 above read Fig. 4.

On the basis of evidence derived from an examination of the contours and from the soil map, three separate aggradational surfaces characterized by distinctive groups of soils are recognized. Fig. 6 showing profiles of the three aggradational fan surfaces, for which the following names are proposed:

Yaldhurst Surface—aggradational surface with soils of Waimakariri group.

Halkett Surface—aggradational surface with soils of Paparua group.

Darfield Surface—aggradational surface with soils of Lismore group.

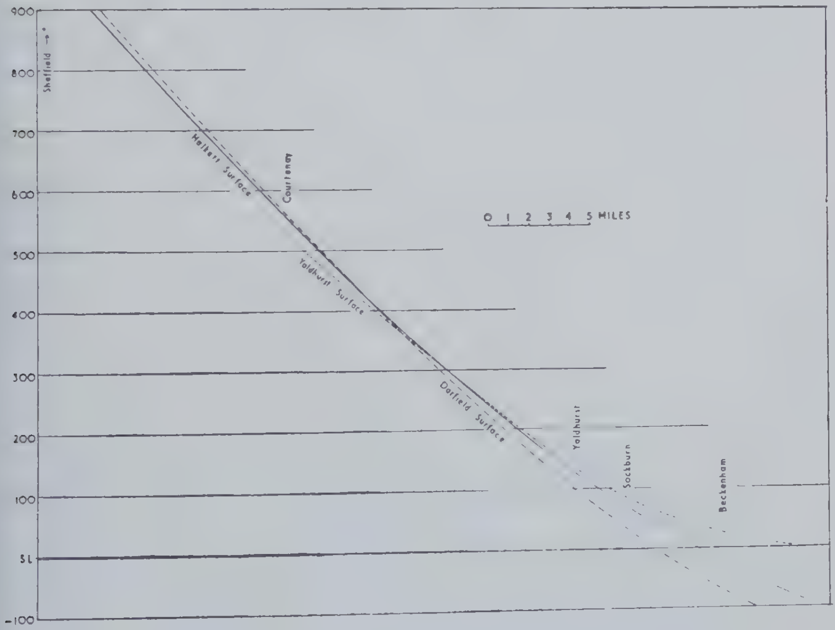

FIG. 6.—Relations between Darfield, Halkett, and Yaldhurst surfaces on cross-section line shown on Fig. 5.

Traced south-eastwards from the lower Waimakariri Gorge, the Halkett surface gradually approaches the level of the Darfield surface. West of Halkett, it is separated from the Darfield surface by a scarp which, when traced to the south-east, gradually fades out, its place being taken by a very shallow depression at the boundary between soils of Lismore and Paparua soil groups. The disappearance of the scarp results from the difference in gradient between the two surfaces, which is such that the Halkett surface lies about 10 ft higher than the projection of the Darfield surface about three miles north-east of Rolleston. A similar relationship exists between the Halkett and Yaldhurst surfaces, the Yaldhurst surface being below the level of the Halkett upstream from the 400 ft contour, but above this level downstream from that contour.

It must be emphasized that unmatched terraces developed during episodes of down-cutting between phases of fan-building are common in the vicinity of the Waimakariri Gorge. Where these have not been buried during later phases of aggradation, they bear soils closely related to—and for this reason on the soil maps cited above, not separated from—those occurring on the next major surface lying above them. An important unmatched terrace lies on the north side of the Waimakariri River south of Burnt Hill. It is 40 ft below the level of the Halkett surface on the opposite side of the river, and has soils of Paparua group developed on it. In the Christchurch area, the Yaldhurst surface has been slightly dissected by the Avon and Heathcote rivers during the last 2,000 years, but these irregularities are not shown on the map.

RADIOCARBON DATES FROM THE CHRISTCHURCH REGION

Nine samples of wood, peat, or shells have been dated by the Division of Nuclear Sciences, Department of Scientific and Industrial Research, and a further three have been found to be beyond the range of radiocarbon dating.

Details for these samples are shown in Table 1 and locations on Fig. 1.

The samples form three groups:

(1) From deposits (Bromley Formation) beneath an important gravel bed (Riccarton Gravel) that underlies the Christchurch Formation, with ages greater than 40,000 years (S 84/505, S 84/516). These are discussed later.

(2) The following sequence, with respect to sea-level, within the Christchurch Formation.

N.Z. Fossil No.	Sample	General locality	Height with ref. to M.S.L. (ft)	Age in years
S84/508	Wood	Cashmere	+ 22	2420
S84/503	Peat	Riccarton	+ 16	3570
S84/506	Wood	W. centre Chch.	+ 16	3720
S84/525	Wood	Linwood	− 3	3810
S84/523	Shells	Riccarton	− 12	6100
S76/505	Shells	Kaiapoi	− 15	6700
S84/522	Wood	City Centre	− 58	8000
S83/501	Wood	Greenpark, Ellesmere	− 73	9400

TABLE 1.—Radiocarbon Dates from the Christchurch Formation.

N.Z. Fossil No.	Grid ref.	N.Z. 14C No.	Locality	Sample	Depth below surf. (feet)	Height with ref. to M.S.L. (feet)	Stratigraphic position	Age (before present)
S76/505	033773		Moore's Pit, Kaiapoi	Shells	30	15±5	Within Christchurch Formation	6,700 ± 90
S83/501	891322		North shore of Lake Ellesmere, 4m east of Selwyn River delta	Wood	75	73	Within Christchurch Formation	9,400 ± 120
S84/503	979560		Bore 236, Mandeville Road	Peat	12	+ 16	Within Christchurch Formation	3,570 ± 70
S84/504	995558		Excavation, Christchurch Hospital	Wood	13	+ 10	Young Meader Fill?	1,550 ± 80
S84/516 S84/505	972594	25	Well 285, Blighs Road	Peat Peat	150 190	105 —145	Top of Bromley Formation	> 45,000 > 40,000
S84/506	995555	27	Excavation, St. Asaph St., nr. Hosp.	Wood	8	+ 16	Within Christchurch Formation?	3,720 ± 100
S84/508	990514*	26	Excavation, Cashmere Hospital	Wood	11	+ 22	Within Christchurch Formation	2,420 ± 100
S84/521	010513		Excavation, Bowenvale Bridge	Wood	8	+ 9	Young Meander Fill	940 ± 70
S84/522	010565		Well 284, corner Madras and Chester Streets	Wood	73	58	Within Christchurch Formation	8,000 ± 150
S84/523 S84/524	972562		Well 303, Clarence Road	Shells Peat	43 137	12 106	Within Christchurch Formation Top of Bromley Formation	6,100 ± 120 > 43,000
S84/525	040567		Excavation, corner Woodham Road and Worcester Street	Wood	14	- 3	Within Christchurch Formation	3,810 ± 70

*Grid ref. corrected *cf.* Fergusson and Rafter, 1957, p. 734.

The samples from 58 ft and 73 ft below sea-level were both taken from woody peat layers which may be accepted as having formed at those places, and comparison of the particular well logs with others makes it almost certain that the peat formation was close to sea-level, as indicated by shells in estuarine or lagoonal beds. The collections of shells at — 15 ft and — 12 ft were both from shellbeds associated with "blue pug," indicating probable estuarine conditions. The wood from — 3 ft with an age of 3810 years (S84/525) was from a single log within a thick bed of blue silt, and was not from its position of growth; nor was the wood from + 16 ft with an age of 3720 years (S84/506), but a comparable age, 3570 years (S84/503), was given to peat at a similar level a mile to the west. The wood from + 22 ft was from a log within sandy gravel, certainly carried down by a river.

(3) Two samples of wood giving the youngest ages, 1550 years (S84/504) and 940 years (S84/521), are from close to the Avon and Heathcote rivers respectively. The latter, from excavations for a new bridge at Bowenvale Road, Beckenham, together with its associated peat, is certainly from young meander fill, and the former may well have had a similar environment.

GENERAL INTERPRETATION OF CHRISTCHURCH FORMATION AND YALDHURST SURFACE

The radiocarbon ages bear out the interpretation of a period of fan-building leading to the development of a young aggradation surface (Yaldhurst surface) at the top of the Christchurch Formation. The ages indicate a rapid rise of sea-level, from — 73 ft to — 12 ft in the period from 9400 (S84/501) to 6100 (S84/523) years ago. At this rate of rise, sea-level probably reached a maximum at or a little above present sea-level (judged by the interpretation of beach gravels within the Christchurch Formation) about 5,000 years ago. This rise of sea-level was so rapid that the pre-existing surface was only slightly modified by wave action, although marine erosion of the gravels that formed the land surface was sufficient to provide beach gravel deposits. As the sea-level rose, the gravel beach moved inland as far as central Christchurch, and when the sea reached a stable level, the beach retreated slightly eastwards. Stability and a possible slight fall of sea-level over a period of several thousand years has permitted progradation of the coastline, and sand flats and dunes now form a coastal belt several miles wide except where the Avon and Heathcote rivers have maintained an estuary. The western margin of this estuary was at first several miles farther west than at present, as shown by the age of 3810 years (S84/525) for wood in blue clay at Linwood. At this stage, the land to the west was being slowly covered up by the development of the most recent fan from the Waimakariri River, which finally built up to the Yaldhurst Surface. Gravels were deposited in the west and sand in the east, and while the lagoon still persisted as far west as Linwood, aggradation had built up the surface in the Riccarton area to a height of 16 ft above the present sea-level. With continuing aggradation, river sand overtopped the estuarine deposits at Linwood and in other low areas behind eastward-retreating sand dunes, and gravels were deposited wherever major flood channels of the Waimakariri extended through the Christchurch area. The age of 2420 years (S84/508) for wood in gravel in the Heathcote Valley at the foot of the Cashmere Hills, 22 ft above present sea-level, gives a maximum age for the development of the Yaldhurst Surface, which may be only slightly younger. Since the formation of this surface, the Waimakariri River, although still tending in exceptional floods to extend across the Christchurch area, as in 1865, has ceased to develop the whole width of its fan, and the Avon and Heathcote rivers have begun to dissect it, forming meanders locally incised to depths up to nearly 15 ft. The failure of the Waimakariri River to continue to develop the whole width of its fan is possibly attributable to a minor drop of sea-level.

Probable slight subsidence of the Christchurch area (see p. 104) makes the figure of — 200 ft for the lowest level of the Christchurch Formation greater than the low sea-level that this figure represents. But sinking is thought not to have been rapid, and as — 200 ft is only the maximum recorded and not necessarily the maximum to which the Christchurch Formation descends, the low sea-level prior to the transgression may well have been of this order. Zeuner (1954) gives — 70 metres (— 230 ft) for the last but one low sea-level and — 30 metres (— 100 ft) for the last. If these figures are of the right order, the transgression that is recorded by the Christchurch Formation began with retreat from not the last glacial advance but the one before. This is compatible with the age of the youngest bed beneath the Christchurch Formation, as deduced later (pp. 116-7). If, however, this age for the time of low sea-level is correct, a fluctuation of sea-level from about — 230 ft to — 30 ft (Zeuner's level for the interstadial between the last two glacial advances) and back to — 100 ft may be undetected before the rise of sea-level to the Flandrian high. The date of about 5,000 years ago for this high sea-level, suggested above, is generally consistent with that of 4,600 ± 70 years (S44/800) for post-glacial estuarine aggradation deposits at Rapahoe, near Greymouth on the West Coast, from which the author collected a wood sample in 1954, and with the ages of 4,350 ± 100 and 4,275 ± 100 years (N.Z. ^{14}C 30, 31, Fergusson and Rafter, 1957) for a probable post-glacial high sea-level in the Hutt Valley (Stevens, 1956).

STRATIGRAPHY OF BEDS BELOW THE CHRISTCHURCH FORMATION

Apart from thin beds described in well logs as "blue" which have been interpreted (p. 105) as indicating reduction of the iron in the presence of carbonaceous material, the beds below the Christchurch Formation are described as brown or yellow. This does not necessarily indicate a high degree of oxidation, the term being more a contrast to the "blue," and the colour is largely imparted by the colour of the sand and clay. The colour descriptions in the well logs give no indication of a stratigraphic break in any well within the beds below the Christchurch Formation, but the absence of an obvious break cannot be accepted as indicating that there is indeed none.

The sequence is illustrated by Fig. 7, a cross-section from Islington east to the coast at South New Brighton. Three features stand out. First, beneath the two western wells the few fine beds, clays with which peats are usually associated, are within exceptionally thick beds of gravels. Second, a consistent thick bed of gravel lies immediately below the surface in the two western wells and below the Christchurch Formation in the eastern wells. This will be referred to as the Riccarton Gravel, as it is normally the first gravel bed encountered in the Riccarton area; the type locality is from 60 ft to 132 ft in the Riccarton Borough Council well (Well S84/236) at Mandeville Road (Fig. 2). Third, the fine beds recorded in the logs of wells from Well S84/223 eastwards comprise more than half the thickness below the Riccarton Gravel. On the line of section, shells in sand are recorded in Well S84/213, between 380 ft and 440 ft below sea-level, and elsewhere shells have been recorded at the following levels below sea-level: 115 ft to 123 ft (Blighs Road, Bryndwyr); 142 ft to 151 ft (Trafalgar Street, St. Albans); 205 ft to 255 ft (Redcliffs); about 220 ft to 260 ft (Cashmere); 405 ft to 407 ft (Burwood).

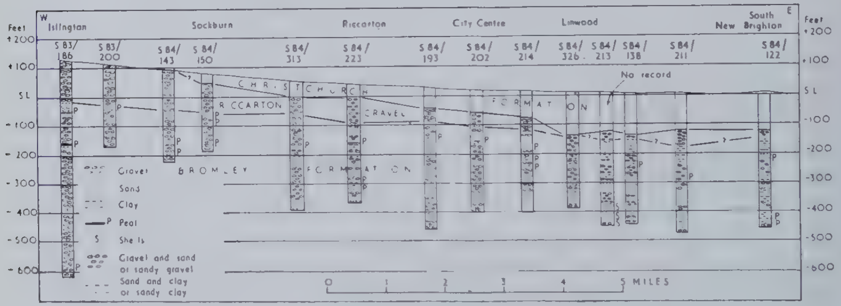

FIG. 7.—Logs of deep wells, illustrating sequences below the Christchurch Formation. For section line, see Fig. 5.

The Riccarton Gravel is interpreted as fluviatile gravel, deposited upon an eroded surface of older estuarine and marine beds in the east and on older fluviatile beds in the west. Figure 8 shows contours, in terms of mean sea-level, on the base of the Riccarton Gravel. In the

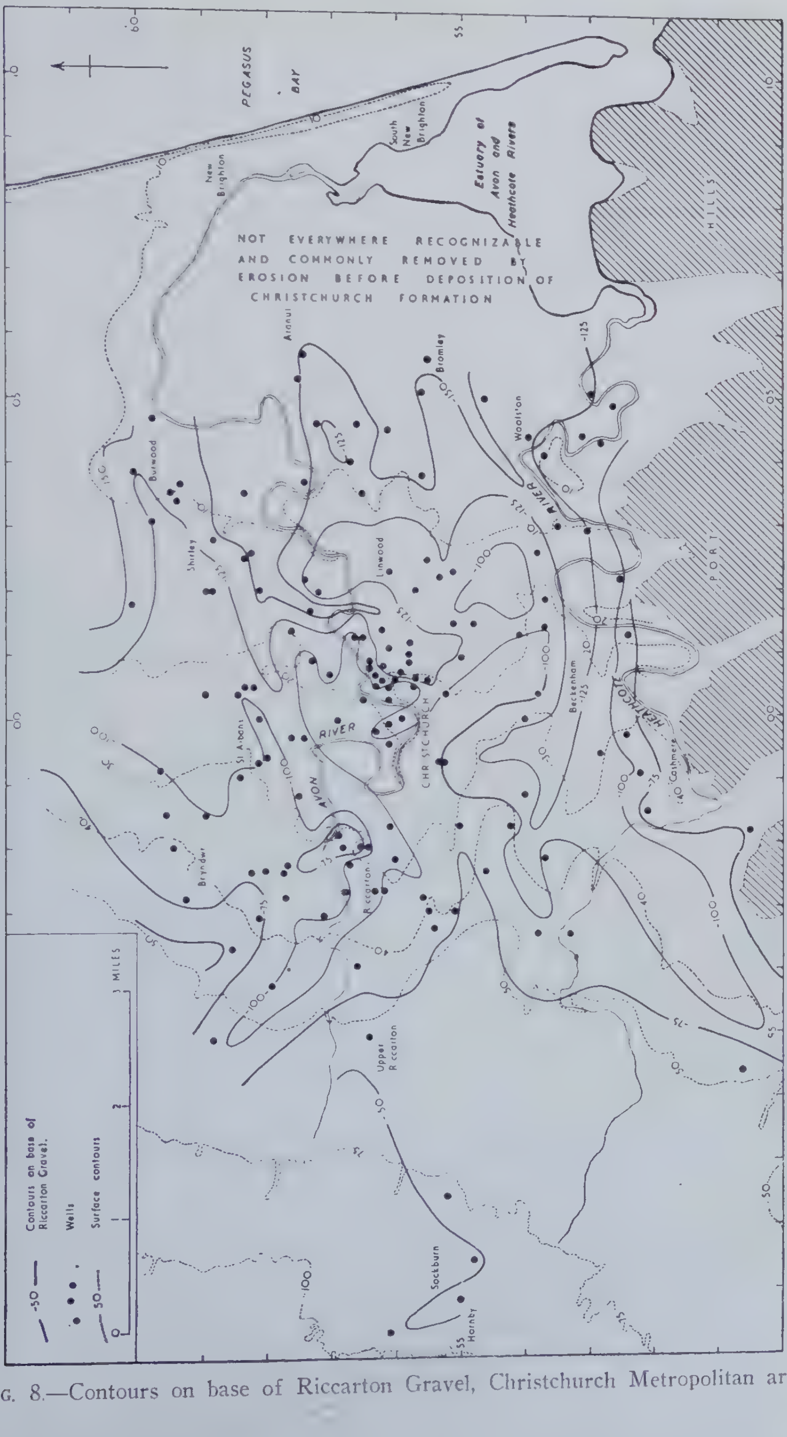

Fig. 8.—Contours on base of Riccarton Gravel, Christchurch Metropolitan area.

east, the Riccarton Gravel cannot be clearly distinguished owing to its partial or complete removal by erosion before the deposition of the Christchurch Formation. The pattern is comparable, in degree of detail and in distribution of the pre-Riccarton drainage channels, with both the pattern beneath the Christchurch Formation and with the present-day drainage pattern, and it seems probable that downcutting into any aggradation surface has a typical pattern in this area. The lack of estuarine or marine intercalations in the Riccarton Gravel implies a shoreline in the east perhaps beyond the present shoreline, at a time of low sea-level, and the gravel was probably deposited as a result of aggradation by outwash streams during a glacial advance—it should be noted that such an origin for the Canterbury Plains in general has long been postulated.

The projections of the Darfield and Halkett surfaces are both higher in level than the remnant of the Riccarton Gravel that is left after erosion prior to the deposition of the Christchurch Formation, but only the Halkett Surface is above it in the three western wells (see Fig. 7). The Darfield Surface would be expected at a depth of about 40 ft in the Islington area, but all the four logs from there record an unbroken top gravel layer from the surface to about 140 ft. If this can be taken to indicate the lack of an old ground surface buried by aggradation to the Halkett Surface (assuming a soil horizon would be preserved and recorded), then the Riccarton Gravel may represent aggradation to the Halkett Surface at a time later than the formation of the Darfield Surface. It has been suggested above that the Riccarton Gravel was formed during a glacial advance, and Dr Maxwell Gage (1958) has recorded two such advances (Blackwater Advances) in the upper Waimakariri Valley, both these being considered to be within a single sub-stage of the "Last" Glaciation. At the western edge of the Plains, about 7 miles north-west of the lower Waimakariri Gorge, the outwash surfaces of the Blackwater advances are not separable, and are about 80 ft below the local representative of the main Canterbury Plains surface, which was formed during an earlier "Last" Glaciation advance (Otarama Advance). Correlation of one of the Blackwater outwash surfaces with the Halkett Surface seems possible. It should be noted that Gage (1958) has recognized an important glacial advance (Poulter Advance) later than the Blackwater, with an outwash aggradation surface plunging below present river levels even before reaching the western margin of the Canterbury Plains.

Below the Riccarton Gravel, which is attributed to aggradation during a Blackwater advance, estuarine and marine beds lie beneath the Christchurch metropolitan area, at least from Well S84/223 eastwards. These beds will be referred to as the Bromley Formation; they are typically shown from 154 ft to 441 ft in Well 138 and from 173 ft to 468 ft in Well S84/211, both in Bromley. They indicate a sea-level rising with respect to the land, and if no tectonic depression is assumed, the sea-level must at first have been more than 450 ft below the present. The deepest well through the Bromley Formation is Well 290, near Spreydon School, about 1½ miles south of Well

S84/223 shown on Fig. 7. It penetrated the Bromley Formation from 140 ft to 701 ft, the following sequence being recorded at the bottom:

(feet)	
573 to 590	Brown gravel and some clay
590 to 605	Blue clay
605 to 607	Blue clay at sand and grit
607 to 609	Blue gravel
609 to 612	Blue gravel and clay
612 to 615	Blue clay
615 to 619	Blue gravel with clay and sand
619 to 661	Blue silty clay with some sand
661 to 664	Blue sand
664 to 668	Blue clay
668 to 672	Blue gravel and sand and clay
672 to 673	Blue gravel and sand
673 to 682	Blue clay (papa?)
682 to 701	Blue clay (softer and more grey in colour)

The lithologies are similar to those higher in the Bromley Formation, in which, apart from blue colour associated with peat beds, all the beds were described as brown or yellow; thus oxidation appears to have penetrated to a depth of 590 ft (550 ft below sea-level). Beneath the Christchurch area, the Bromley Formation gives no indication of other than a marine or estuarine environment, as suggested by the abundance of fine beds and the records of shells at many levels, and before deposition began sea-level may have been at least 650 ft below the present level of the bottom of Well S84/223; the Bromley Formation was presumably formed during rise of sea-level after a glacial retreat. In the western part of the section (Fig. 7), the apparently unbroken gravel from 180 ft to 580 ft below sea-level in Well 186 is less likely to have been deposited in a near-shore environment. It may be older than the Bromley Formation to the east, and may represent fluviatile aggradation gravels deposited by outwash rivers when the sea-level was low and the coastline far to the east. But it is not clearly enough differentiated from the Bromley Formation to justify a separate formation name.

Zeuner (1954) gives — 100 metres (— 330 ft) as the lowest sea-level during the "Last" Glaciation, and — 200 metres (— 660 ft) during the "Penultimate" Glaciation. Thus the Bromley Formation appears to have been formed during the major interglacial between these two glaciations, as seems probable from the ages of more than 40,000 years for samples (S84/505, S84/516) from the top. Since oxidation extends down to 550 ft below present sea-level, and the lowest "Last" Glaciation sea-level given by Zeuner (1954) is — 100 metres (— 330 ft) this implies, since oxidation is unlikely below the water table, downwarping of at least 220 ft since the early part of the "Last" Glaciation. Accepting a "Last" Interglacial age for the Bromley Formation, the thick fluviatile gravels in Well 186 are probably of "Penultimate" Glaciation age.

If the correlation of the Riccarton Gravel with the Blackwater glacial advance is correct, the gravels whose top forms the Darfield Surface are unrepresented beneath Christchurch city, since the surface, correlated with the outwash surface from the Otarama Advance, is almost certainly of "Last" Glaciation age, in contrast to the probable "Penultimate" Glacial or "Last" Interglacial age of beds beneath the Riccarton Gravel. Perhaps the gravels beneath the Darfield Surface were thin, as is the Riccarton Gravel, and were eroded from the Christchurch area prior to the deposition of this latter gravel. In this case, the available radiocarbon dates gave no indication of the age of the Darfield Surface, the main aggradation surface of the Canterbury Plains.

Summary of the Late Quaternary Geological History

The sequence of deposits is summarized in Table 2. It begins with gravels, probably of "Penultimate" Glaciation age, deposited in front of an ancestral Waimakariri Glacier. On retreat of the ice, these outwash gravels were cut back rapidly by the sea at a level of perhaps as much as 650 ft below the present, and when the sea-level subsequently rose, the Bromley Formation, estuarine and marine gravels, sands, silts, and peats accumulated in the shelter of Banks Peninsula: these are known to be more than 43,000 years old (S84/516, S84/505), and are probably of "Last" Interglacial age. With lowering of sea-level during the first of three later glacial advances, all of "Last" Glaciation

Table 2.—Correlation of Canterbury Glacial Chronology, Fan Surfaces, and Formations of the Christchurch Metropolitan Area.

	Canterbury glacial chronology (Gage, pers. comm.)	Fan aggradation surfaces	Formations
"Last" Glaciation	Poulter Advance	Yaldurst Surface —	Christchurch Formation
	Blackwater 1 and 2 Advances	Halkett Surface	Riccarton Gravel
	Otarama Advance	Darfield Surface	
	Woodstock Advance		
"Last" Inter-glacial	Downcutting and weathering		Bromley Formation
"Pen-ultimate" Glaciation	Avoca Glaciation		?Lower Gravels of Well S83/186

age, local streams presumably cut down into the earlier sediments, before a new fan of outwash gravels carried by the Waimakariri River filled up the valleys and finally built up gravels to the Darfield Surface. These gravels do not appear to have been preserved in the sequence below Christchurch, but the Riccarton Gravel represents part of an outwash fan formed during a second important advance during the "Last" Glaciation. As the glaciers retreated, the rivers cut down to at least 200 ft below present sea-level, and subsequently, as sea-level rose, the coastal marine and estuarine part of the Christchurch Formation was deposited. A third glacial advance during the "Last" Glaciation, known only from the upper Waimakariri Valley, probably caused an important fluctuation of sea-level, but no break in the Christchurch Formation has been detected. The final rise of sea-level is known to be post-glacial in age, being dated 9400 years ago (S84/501) 73 ft below present sea-level and 6100 years ago (S84/503) 12 ft below. Assuming a constant rate of rise, the sea reached a little above its present height about 5,000 years ago. Aggradation by the Waimakariri River caused by rising sea-level produced a fan that extended over the Christchurch area at the time of maximum sea-level. Its surface, the Yaldhurst Surface, has since been slightly dissected by the Avon and Heathcote rivers, probably during a slight fall in a level during the past two thousand years.

ACKNOWLEDGEMENTS

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LATE PLEISTOCENE GLACIATIONS OF THE WAIMAKARIRI VALLEY, CANTERBURY, NEW ZEALAND

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Summary

Five distinct periods of major ice advance recorded in the Waimakariri Valley by a variety of glacial and glacifluvial deposits are distinguished by differences of elevation, surface gradients, distribution, weathering, and extent of defacement of original surface detail. Glaciations are grouped and named as follows: Avoca Glaciation (probably multiple, but not subdivided); Waimakariri Glaciation (comprising in chronological order Woodstock, Otarama, Blackwater, and Poulter advances, of which at least the last two were multiple). Interglacial deposits are rare. The Waimakariri glacier system was a complex pattern of ice streams, including large tributaries mainly from the north-west and distributaries between which transfluence occurred through numerous saddles. The ice in the middle reaches of the main valley was about 4,000 ft thick during the Avoca Glaciation, and perhaps from 500 ft to 1,000 ft thick at the height of later advances. Glacial geomorphic features are essentially the work of the later advances. The Avoca Glaciation, which was the most extensive, corresponds with the Waimaungan Glacial Stage and dates from early in the second half of the Pleistocene. An interglacial stage separates it from the last four advances, which together represent locally the Otiran Glacial Stage. The Otarama advance was the last occasion when ice reached as far as the eastern margin of the mountains, and outwash gravels from this advance built most of the Waimakariri segment of the Canterbury Plain. Several lakes existed temporarily during recessive phases, the largest lake having been at least 10 miles long in the main valley upstream from Poulter River.

Introduction

Location

This paper is concerned mainly with the eastern half of the Broken River Sheet (S66, unpublished) of the N.Z.M.S. 1 Topographical Map Series, equivalent to Grasmere Survey District together with portions of adjacent survey districts. This sparsely populated mountainous tract extends from the inner margin of the Canterbury Plains northwards to within a few miles of the Southern Alps main divide, and the highest peaks within it exceed 6,000 ft. The Christchurch-Greymouth Railway and the Arthurs Pass highway to the west coast provide access, but there are few other roads. Continuous beech forest covers the mountain slopes up to the timberline near the northern boundary, but elsewhere the area consists of tussock grassland, scrub, bare rock, scree slopes, and broad, gravel river beds, with discontinuous patches of the formerly more extensive beech forest.

The headwaters of the Waimakariri River and several of its major tributaries drain a segment of the main divide. Comparatively narrow ice-modelled trough valleys accommodate the upper reaches of the Waimakariri as far down as the mouth of Crow Stream and the larger tributaries entering from the north and north-east (Crow, Bealey, Hawdon, Andrews, Poulter rivers). The main valley widens downstream from the Crow junction, and sweeps in curves of large radius down to the mouth of Esk River. Cross-profiles of the main trough are asymmetrical at the curves, having decidely gentler slopes on the outside of the curve. Below Esk River the main stream enters a narrow winding rocky canyon about 7 miles long, hereinafter referred to as the "upper gorge", which is river-cut to depths of more than 1,000 ft beneath the surface of glaciated uplands. The upper gorge ends near the mouth of Broken River, which drains Castle Hill Basin and the eastern slopes of the Craigieburn Range. Downstream from Broken River the Waimakariri is entrenched about 200 ft below the floor of a formerly glaciated though rather sinuous trough between the ends of the Puketeraki and Torlesse ranges, which will be referred to as the "Staircase gorge". Emerging from the mountains near Kowai Bush, the Waimakariri flows south-eastwards and then eastwards across the Canterbury Plain in a trench, which shallows progressively as the profiles of plain and river bed converge. This trench is broad except at the "lower gorge", near Sheffield, where the river is superposed upon a ridge of hard rocks buried beneath the alluvium underlying the plain.

Earlier Work

Glaciation within the Waimakariri watershed was discussed by Haast (1879), Hutton (1884), and Gudex (1909). Several papers by Speight (esp. 1916, 1917, 1935, 1938) refer to the glacial landforms and deposits of the region. Although well acquainted with evidence for multiple glaciation in the northern hemisphere and with the views of other authors in favour of at least dual glaciation in New Zealand (e.g., Henderson, 1917, 1931; Morgan, 1926), Speight saw no convincing evidence in the Waimakariri Valley for significant interglacial episodes. He considered that the glacial deposits were adequately explained by irregular retreat from a maximum advance of ice possibly as far east as Racecourse Hill near Sheffield, with halts and even minor re-advances, but never a warm interglacial period. Eventually, Speight (1938, p. 151) recognized stratigraphic evidence for an appreciable ice recession followed by re-advance, but this episode appears now to have been insignificant compared with an interglacial stage and several interglacial substances for which evidence is presented in this paper.

Objects of this Study

An opportunity to observe the kind of evidence upon which a theory of multiple glaciation has been established in the Cordilleran region of North America demonstrated to the author that some of the criteria could be adapted and applied in New Zealand. After his return, numerous brief excursions and a few longer visits to the Waimakariri

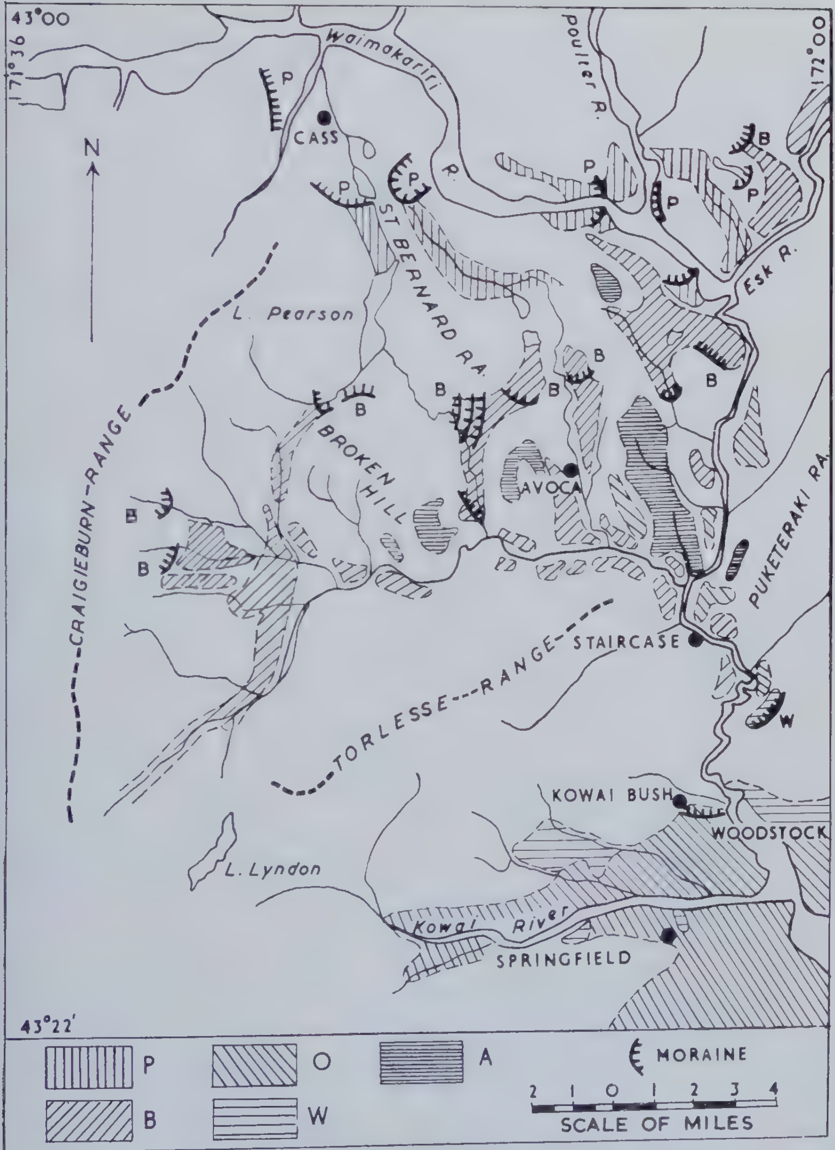

Fig. 1.—Map showing late Pleistocene deposits in the middle reaches of the Waimakariri Valley. A = Avoca Glaciation; W = Woodstock Advance; O = Otarama Advance; B = Blackwater Advance; P = Poulter Advance.

watershed re-inforced the author's earlier doubts as to the adequacy of a monoglacial scheme in this region. The purpose of this paper is to describe and map the moraines and glacifluvial deposits and other glacial features, and to present the hypothesis that, during the late Pleistocene, the area experienced a succession of major glacial advances separated by partial or total withdrawals of ice, including one long interglacial interval. The extent and variety of glacial deposits will be evident from Figs. 1 and 2.

The Pre-Pleistocene Rocks

Most of the Waimakariri watershed is occupied by folded and faulted Triassic indurated greywacke, siltstone and argillite, chert and volcanic rocks, which increase perceptibly in induration north-eastwards towards the main divide. Poorly rounded blocks of the more highly indurated types occurring in deposits in the lower reaches of the river are therefore good evidence of glacial transportation. Infolded or infaulted strips of Cretaceous and Tertiary rocks are preserved in structural depressions due to mainly late Tertiary or early Pleistocene deformation. Castle Hill Basin contains the largest of these outliers. (Speight, 1915, 1917, 1920; Grindley, 1951; Gage, 1956). Coal, as pebbles and sand, is the only derivative of the younger rocks yet recognized in the glacial deposits, although calcareous matrix in glacifluvial sediments near Avoca (to be described later) may have originated by glacial erosion of nearby Tertiary limestone. No constituent foreign to the terrain of the present Waimakariri watershed has been found, nor is there any obvious petrological difference between deposits from different ice advances.

OUTLINE OF PROPOSED CHRONOLOGY

The sequence of ice advances and withdrawals indicated by the deposits in the Waimakariri Valley form part of the basis for a recently-proposed scheme* for New Zealand glacial stages (Gage and Suggate, in press). Correlation between the local terminology and the proposed stages is given below.

	(Post–glacial)	
Waimakariri Glaciation	Poulter Advance *(Short interglacial interval)* Blackwater–II Advance *(Brief recession)* Blackwater–I Advance *(Interglacial interval)* Otarama Advance *(Rel. long interglacial interval)* Woodstock Advance	OTIRAN GLACIAL STAGE
	(Long interglacial interval)	(INTERGLACIAL STAGE)
Avoca Glaciation	(Possibly multiple)	WAIMAUNGAN GLACIAL STAGE

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*The scheme was introduced in a joint contribution before Section C of the 32nd Meeting, Australian and New Zealand Association for the Advancement of Science, Dunedin, January 1957.

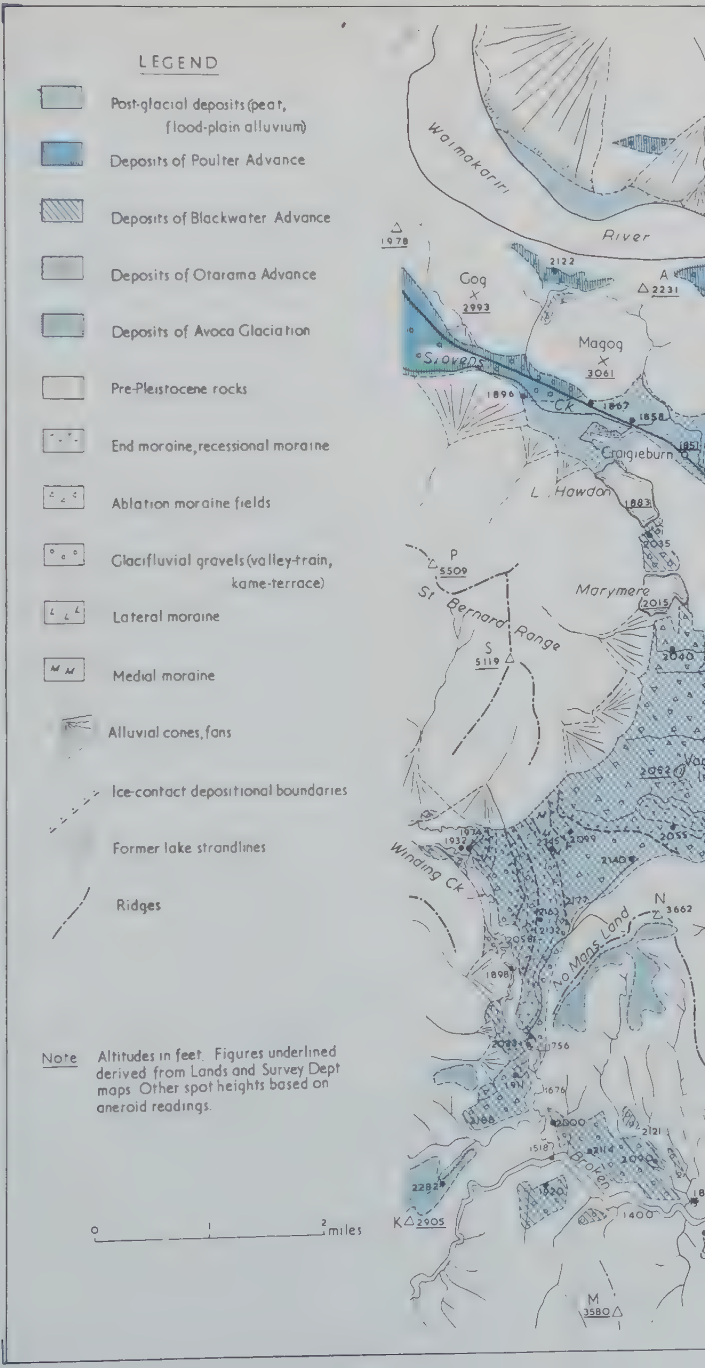

FIG. 2.—Glacial deposits in t

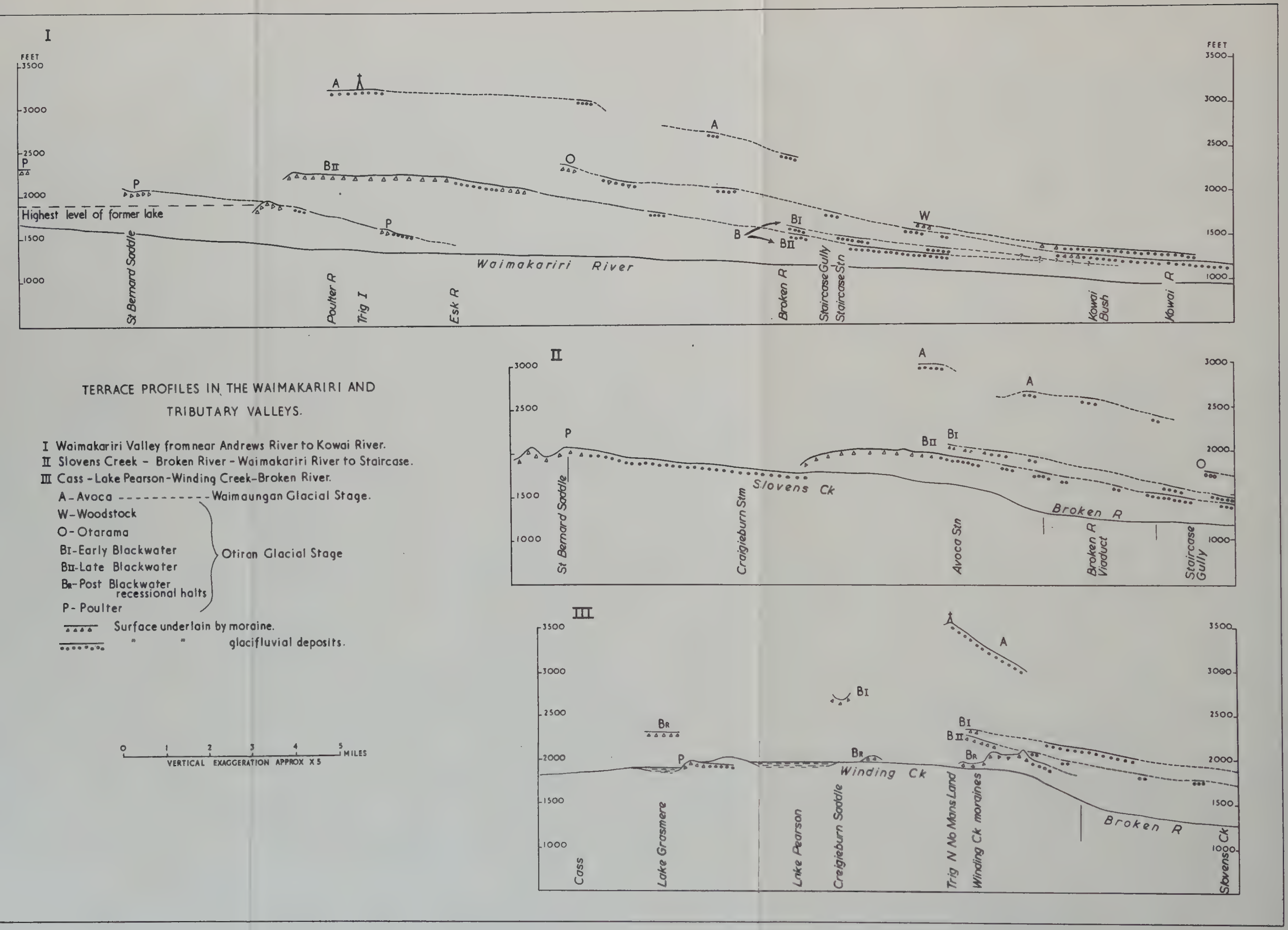

FIG. 3.—Terrace profiles in the Waimakariri and tributary valleys.

The first two advances of the Waimakariri Glaciation thrust beyond the mountains into the western fringe of the piedmont area, but not as far as the maximum of the Avoca Glaciation. Later major advances were less vigorous, reaching only within 8 to 15 miles of the mountain front (Fig. 7). The Woodstock-Otarama interval may have been longer and warmer than subsequent interglacial intervals, but it was much shorter than the pre-Woodstock interval. Direct evidence for pre-Avoca glaciations is wanting, but the Canterbury region is unlikely to have escaped the early Pleistocene cooling, which caused glaciation in Westland (Ross Glaciation:, Wellman, 1951; Gage, 1945; Fleming, 1956). Parts of the Kowhai Gravels are probably co-eval with the Ross glacial beds (Lower Nukumaruan) and may therefore be glacifluvial in origin.

DISTINGISHING BETWEEN ADVANCES

Differences of elevation, distribution, depth, and intensity of weathering, and defacement of original surface detail were used to distinguish the deposits from different advances. Unconformity between Avoca and younger drift can be seen at a few places. The value of the height-difference criterion may be judged from Fig. 3, which shows the clear vertical separations and gradient differences between successive moraines and glacifluvial terrace surfaces. Oxidation distinguishes Avoca and Woodstock deposits from all younger drift. Avoca deposits are distinguished from Woodstock by height differences and also by deeper weathering, thicker and more extensive loess cover, and more drastic solifluction effects on Avoca surfaces. Altitude and gradient distinguish Otarama from Blackwater. Poulter deposits had the smallest original extent, occur at the lowest levels, are fresh and unweathered, and retain fine details of surface form. All pre-Poulter glacial deposits that escaped subsequent ice-erosion have suffered from frost action and solifluction to varying degrees, so that even Blackwater deposits have lost some sharpness of original surface detail. Frost action has eliminated all but the largest protruding morainic boulders and rounded the profiles of the moraines. Woodstock terraces are cloaked by soliflual head deposits, and Avoca surfaces are dissected by gullies and degraded by solifluction so that little of the original surface remains.

Glacial sculpture of greywacke rock surface survives to varying degrees depending chiefly upon the time that has elapsed since the surface was ice-abraded. Thus, pre-Otarama sculpture, shown for example by the upper trough walls above the upper and Staircase gorges, is so greatly modified by non-glacial destructive processes that, if it were not associated with glacial sediments, its glacial origin might be questioned. Surfaces last trimmed by Blackwater ice, such as the upper northern slopes of the Black Range near Bealey, are corrugated by post-glacial rills, but surfaces abraded by Poulter ice are fresh and undissected, except by gullies formed by the concentrated attack of vigorous streams of post-glacial run-off. Fine grooving and glacial striae can be found only on Poulter-glaciated surfaces. Fresh Poulter ice sculpture is particularly obvious on the eastern valley wall between Andrews and Poulter rivers.

Organic interglacial deposits are rare. Fossil wood and peat in laminated silts underlying Otarama glacifluvial gravels are believed to mark milder conditions in the Woodstock-Otarama interval, but further paleobotanical studies are required. There is wide scope for further testing of the present chronological scheme by other special techniques, including clay mineralogy of fine fractions of sediments to determine age-differences and depth of weathering, but the chronology is essentially based on field relations.

FIELD PROCEDURE

No adequate topographic map existed, so that it was necessary to compile a new base map on a scale of one inch to a mile, adding additional detail from air photographs, to show the extent of moraine and other deposits. In the field, remnants of original constructional surfaces produced by outwash valley-train aggradation were sought, and distinguished from surfaces of other origin such as those carved by river planation in glacifluvial gravels. Where the latter have been planed indiscriminately across bed-rock and gravels, channelled and stepped by flights of low terraces, and veneered by lag-accumulations of coarser gravel, they are readily recognisable. Outwash surfaces, where still connected with terminal moraines, could be identified positively; where underlain directly by thick glacifluvial deposits and pitted with kettle-holes, they could be identified with high probability. In some places there remained doubt as to whether particular terrace-remnants had been degraded by stream planation, but cut-terrace remnants tend to have steeper gradients than outwash surfaces.

Stream dissection during and after deglation has reduced most outwash surfaces to discontinuous lengths of terrace, which were correlated where possible first by sighting by eye, and then by taking barometric height observations from which to construct profile sections (Fig. 3). Proglacial outwash and lateral meltwater channel deposits due to different glaciations were distinguished by these means, and traced down-valley through the gorges and linked with the Canterbury Plain and older piedmont alluvial surfaces. Aneroid observations in this mountainous region are subject to error from abrupt local variations of barometric pressure, aggravated by the length of travelling time between the few available height-control points. The error was reduced as far as possible by re-occupying some stations on different days, but isolated stations are perhaps as much as 25 ft in error. Fortunately, the vertical intervals between the main systems of terraces proved to be generally of a larger order than the likely error, and in the writer's opinion the correlations are reliable.

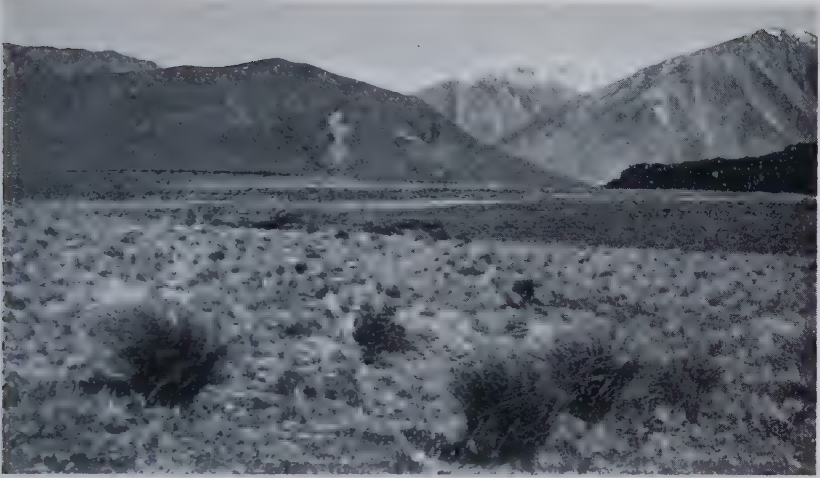

FIG. 4.—Surface of Avoca Plateau at 2,600ft near western edge 1½ miles east of Avoca railway station.

AVOCA GLACIATION

Name

The name relates to the location of the thickest surviving deposits from this glaciation beneath an undulating plateau, rising to between 2,600 ft and 3,200 ft east of Avoca, and referred to in this paper as "Avoca Plateau" (Fig. 4). (In earlier unpublished accounts the writer has referred to this glaciation under other provisional names, including "Trelissick" and "Deepdrift".)

Ice Extent and Thickness

At the maximum of the glaciation, ice filled the entire Waimakariri catchment, including Castle Hill Basin and possibly Esk Valley. As asserted by Haast (1879, p. 392) and more diffidently suggested by Speight (1935, p. 309), the Waimakariri and Rakaia glacier systems were joined by transfluence through Coleridge Pass and Lake Lyndon saddle, and they may also have coalesced in the piedmont area south-east of Malvern Hills. All the main valleys were probably filled by interconnecting ice, through which the higher ridges and summits protruded as nunataks. Impounded by the Puketeraki and Torlesse ranges, the Waimakariri sector of this reticular glacier (Charlesworth, 1957, p. 84) overflowed south-eastwards through a gap (Fig. 5), perhaps enlarged and straightened from a pre-existing river valley, beneath the floor of which the sinuous course of the present Staircase gorge of the Waimakariri is entrenched roughly 1,000 ft. The Avoca ice-discharge gap is clearly seen from viewpoints on the Canterbury Plain near Springfield. Avoca ice overrode the lower flanks of Malvern Hills and reached beyond Sheffield, but its farthest limits are unknown (Speight, 1938, p. 157).

The maximum thickness of ice is not known directly, but some inferences may be drawn. Ice certainly reached higher than Trig. I (Grasmere S.D.; 3,244 ft) and No Mans Land (3,662 ft), and since the deposits on these summits show no signs of having been overtopped by later advances, it may be inferred that traces of glacial sculpture at still higher levels up to about 5,000 ft are to be ascribed to the Avoca Glaciation. Glacifluvial deposits extend below present river-level in the upper gorge at about 1,200 ft altitude, so that the effects of Avoca ice may be said to range vertically through about 4,000 ft. Although there is no certainty that the highest and lowest signs of Avoca ice action were produced contemporaneously, the erosional and depositional results are on so large a scale that a maximum ice thickness of 4,000 ft is no more than reasonable.

Deposits

It is clear that erosion has reduced an extraordinarily thick and extensive accumulation of glacial sediments of all types to small remnants surviving either above the level reached by later ice advances or in lower situations where protected in narrow gutters or in the lee of rock-barriers transverse to later ice streams. The remnants cover about 6 square miles in the main valley and Castle Hill Basin, and reach a maximum thickness (estimated from a composite section) of 1,400 ft beneath the Avoca Plateau. Avoca beds north of Broken River near

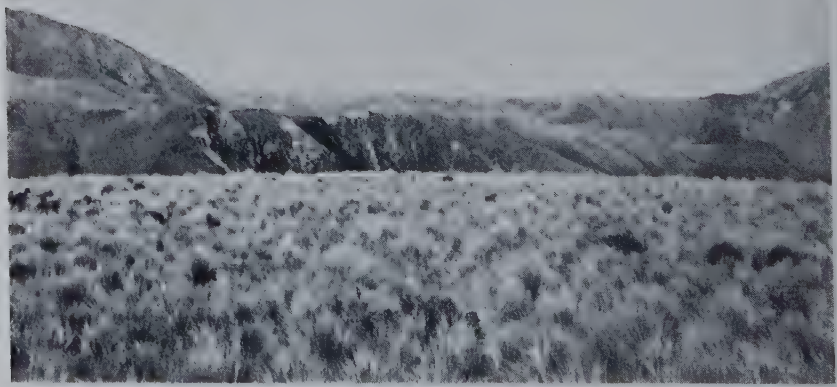

FIG. 5.—View south from southern end of Avoca Plateau at about 2,500 ft, showing course followed by Avoca outlet glacier between the ends of Puketeraki (left) and Torlesse (right) ranges. Upper Waimakariri gorge crosses centre of picture. Light patches below crest of ridge beyond gorge are exposures of very coarse angular Avoca gravels.

the mouth of Winding Creek are at least 400 ft thick, whereas on the summit ridge and southern slopes of No Mans Land and on the small plateau of Trig. I no more than a few tens of feet may be present. The crest of a spur east of the upper gorge opposite the mouth of Broken River is capped at about 2,400 ft by coarse morainic gravels, and Avoca beds crop out beneath later gravels in the lower gorge of Broken River and in Slovens Creek and some of its branches. East of the Alpine foothills, weathered and deeply loess-covered gravels are found on terraces and the ends of spurs around the base of Malvern Hills. These gravels, together with the morainic gravels of Racecourse Hill and Sheffield Mound (Hutton, 1884, pp. 449-54; Speight, 1928, map; 1938, pp. 154-56) are considered to be the remains of a former outwash sheet joining with similar outwash deposits from other valleys to form a piedmont alluvial plain analogous with the Canterbury Plain. From their elevation, these deposits are of pre-Woodstock age, and were most probably formed during the Avoca Glaciation.

Avoca deposits include till, ice-contact deposits, sub-glacial water-laid gravels and sands, varved silts, and outwash gravels. No component foreign to the Waimakariri watershed has been detected. Coal pebbles up to 1 in. in diameter and coal sand present in laminated silts at Avoca are ascribed to contemporary glacial erosion of nearby Cretaceous coal measures, but the rarity of Tertiary basalt and limestone fragments is remarkable. More extensive exposures show marked lateral variations in texture and highly irregular stratification. The higher portions consist of rather coarse outwash gravels, whereas till and varved silts are confined to near the base. The middle portion is composed of irregular lensoid masses of cross-bedded, well rounded, fairly fine gravel and sand. Striated pebbles are found only in the basal till and as inclusions in varved silts.

An unnamed stream which rises on the Avoca Plateau and joins the Waimakariri River half a mile upstream from Broken River junction gives the best available evidence for original thickness and a composite section of Avoca beds, as follows:

(ft)	
(18+	supposed soliflual debris.)
10	chiefly yellow-brown gravel and silt, decomposed and leached in patches, irregular iron-pan (? weathering profile).
25	brown, oxidized, poorly sorted outwash gravel, boulders up to about 1 ft, grading down to:
300±	brownish-grey similar outwash gravel.
	(section obscure for about 20 ft.)
20	brown-stained stream-bedded sand.
	(section obscured; interval uncertain.)
500-700	irregularly stratified, brown, poorly sorted, mostly fine, gravel and sand; lenses of laminated silt and sand; discontinuous exposures.
100±	fresh grey well rounded fine gravel; bedding irregular and locally distorted: silt pebbles near base; abundant fine silty matrix.
6±	fine fresh pebbly till.

The surface of greywacke basement is extremely irregular, in some places projecting upwards for several hundred feet into the glacial beds, as sharp ridges. Effects of contemporaneous ice-pressure, melting-collapse, differential compaction and settlement on uneven substratum are seen in the irregular stratification and locally steep and variable dips of sub-glacial and pro-glacial ice-contact deposits formed as Avoca ice withdrew from an unevenly overdeepened basin. The upper gravel portion may have originated as proglacial outwash from a later re-advance of limited extent, so that the Avoca Glaciation was perhaps multiple.

The lower Avoca beds are most accessible in Slovens Creek near Avoca. Here thinly-bedded silt with coal-sand laminae unconformably underlies Blackwater–II outwash gravel, the contact being traceable some distance up the valley by ground-water seepage and a vegetation-line due to the lower permeability of Avoca beds. At the mouth of Puffers Creek the following section is exposed:

(Post-Blackwater fan of Puffers Creek)

……

laminated brown sand
laminated grey silt
fine pebbly till with striated stones (fresh)
lens of stream-bedded fine compact gravel with abundant calcareous silty matrix

……

(Lower Tertiary glauconitic sandstone)

Thicknesses vary abruptly, and the beds are locally in the form of an open syncline with its axis parallel to Slovens Creek valley. A few chains farther downstream there is no sign of folding in Avoca beds, and the deformation is therefore ascribed to local slumping and collapse due to melting of embedded ice, or of lateral supporting ice. The texture of the underlying silty gravel resembles that of an esker deposit.

Varved silt containing striated stones and discoidal concretions grading up to laminated sands dipping 20°W crops out in a gully draining into Slovens Creek from the west, $\frac{1}{4}$-mile below Puffers Creek. From 4 ft to 6 ft of pebbly till separates the varves from underlying Tertiary sediments which include greasy clay members. Gravitational slumping promoted by these clays could account for the comparatively steep dip of the Avoca beds, as well as for the rotation and back-tilting of the overlying Blackwater–I morainic gravels and slight back-tilting of their upper surface.

A thickness of several hundred feet of middle Avoca beds is continuously visible (though not easily accessible) on the north side of Broken River half a mile below the railway viaduct. Other small areas of these beds are exposed alongside and below the railway near the viaduct.

Age

Except for the lower layers, which are rich in fine impermeable silt, Avoca beds are moderately or strongly oxidized throughout. Gullies dissecting the southern end of the Avoca Plateau show particularly well the depth and intensity of oxidation, and some show what appears to be an old weathering profile beneath the plateau surface, cloaked in places by sheets of soliflual debris that has drifted down from higher parts of the plateau during more than one cold phase. The present severe winter conditions on the plateau suggest that during post-Avoca glaciations it would have been an area of periglacial frigidity (Fig. 6).

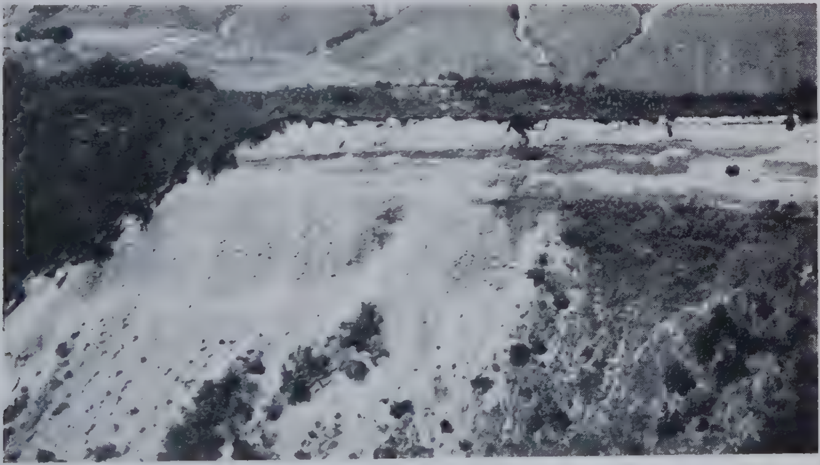

Fig. 6.—Wedge of loess and solifluvial debris resting on bench in Avoca outwash gravels near south end of Avoca Plateau, stream-planed during the post-Avoca interglacial interval.

These considerations tend to support the view that Avoca beds are not only the oldest glacial deposits in the valley, but that they are considerably older than the remainder. Their age, however, is limited by tectonic factors. The marine Tertiary succession in coastal north Canterbury concludes with littoral beds followed by thick non-marine conglomerate (Kowhai Gravels), the upper part of which is Nukumaruan (early Pleistocene) in age, and the whole sequence is involved in folding and faulting, which initiated the strongly tectonic landscape. Conglomerates of uncertain age, but possibly correlated with Kowhai Gravels, are present in the Esk Valley and in the Harper Valley west of the Craigieburn Range. These are strongly deformed and were involved in at least the later stages of the tectonic movements responsible for the formation of Castle Hill Basin and other intermontane depressions (Speight, 1915, pp. 341-5). Moreover, early Pleistocene strata in Westland, including the Ross glacial beds, are strongly deformed (Gage, 1945). But the Avoca beds have suffered no appreciable tectonic deformation, and furthermore they were deposited within the framework of tectonic landforms after the orogenic movements had subsided. Probably, therefore, they were formed early in the second half of the Pleistocene. If older, deformation would be expected; if younger, there would hardly have been adequate opportunity for the weathering and erosion, which is so much more pronounced than in any of the younger sets of glacial deposits in the Waimakariri Valley.

The products of the Avoca glaciation are part of the basis for the Waimaungan Glacial Stage (early part of Late Pleistocene; Gage and Suggate, in press).

INTERGLACIAL INTERVAL

During the interval between the end of the Avoca Glaciation and the next recorded advance of ice, Avoca deposits were deeply dissected and the Staircase gorge of the Waimakariri River was incised down to the level approximately of the Christchurch-Greymouth Railway grade, which is about 1,000 ft lower than the floor of the Avoca ice channel. The upper gorge was not cut until later. Warm, humid conditions over a long period, longer than the intervals between and since later glaciations, must be postulated to explain the deeply oxidized condition of Avoca beds, and the post-Avoca interval is therefore regarded as of the magnitude of a full interglacial stage—perhaps equivalent to the Last Interglacial or Sangamon Stage of the northern hemisphere. No interglacial deposits have been found.

The view that the Staircase gorge did not exist during Avoca time depends upon the following admittedly negative evidence. Although Avoca deposits are present at low levels in narrow rock-bound and presumably glacially-overdeepened depressions near Broken River junction, none is showing in the Staircase gorge, where the circumstances are favourable for observing them if present. The present gorge is unlikely to be a re-excavated gutter of Avoca age, since it is usual for re-excavated channels to become superposed on exhumed rock spurs partly off the course of the original channel, which is thus recognizable from sections of infilled gutter cutting across spurs. No such gutters are present in the Staircase gorge.

WAIMAKARIRI GLACIATION

The more obvious effects of glacial erosion and the bulk of the surviving glacial deposits in the South Island are due to ice advances of the Otiran Glacial Stage, which in Canterbury are especially clearly differentiated in the Waimakariri Valley (Fig. 7). It is therefore ap-

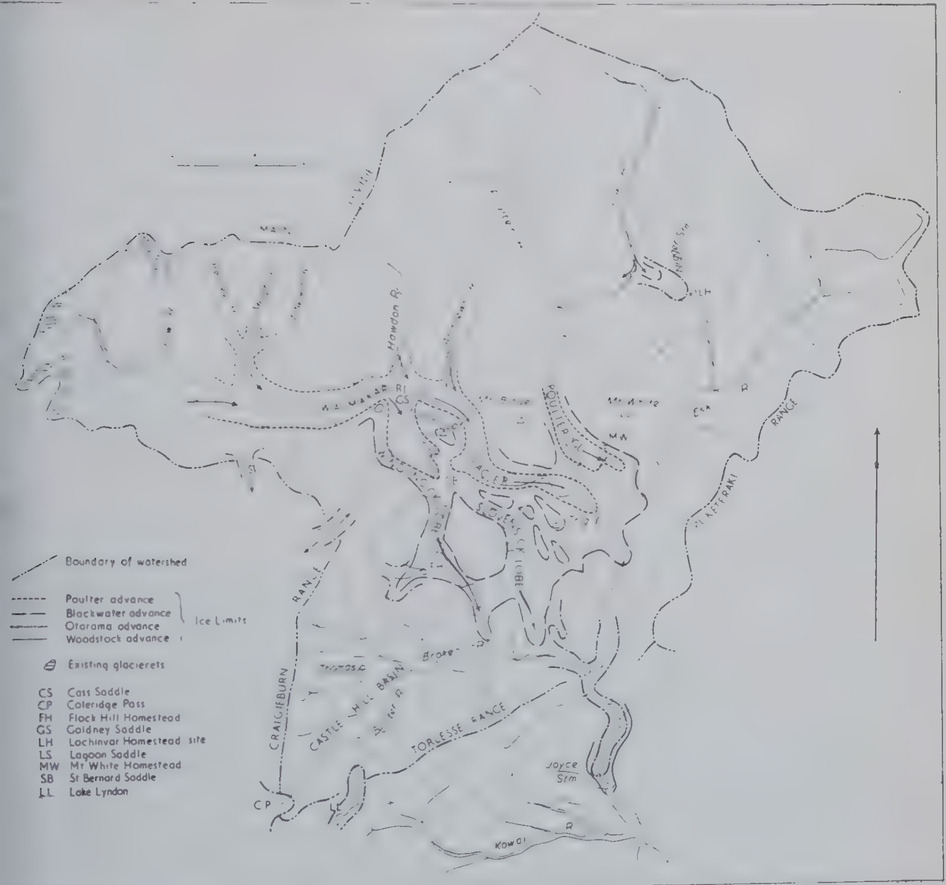

FIG. 7.—Map of Waimakariri montane watershed, showing main ice streams and inferred limits of ice advances during Waimakariri Glaciation (Otiran Glacial Stage). Note (1) Upper reaches of all main valleys except the Esk and Broken Rivers were more or less completely ice-filled at the maximum of each advance; (2) heads of all major streams rising on the eastern slopes of Craigieburn Range were occupied by glaciers during all pre-Poulter advances, but ice-limits have not yet been located precisely in this area.

propriate to group the four advances (herein named Woodstock, Otarama, Blackwater, and Poulter) together under the local name Waimakariri Glaciation, covering a period comparable with the northern hemisphere "Last Glacial", but perhaps extending farther back than "Wisconsin" in the strict sense (Gage and Suggate, in press).

WOODSTOCK ADVANCE

Name

The name is taken from Woodstock Station at the lower end of the Staircase gorge, where the relations of the deposits are most clearly seen.

Ice Extent and Thickness

The maximum extent of Woodstock ice is uncertain, but below Broken River the Waimakariri glacier of this time was certainly confined within the post-Avoca Staircase gorge (Fig. 8), and there is no evidence that it reached beyond the Springfield area or that it occupied Castle Hill Basin. Neither this nor any subsequent advance overtopped Trig. I hill or the Avoca Plateau. Scant survival of Woodstock deposits is consistent with the view that the subsequent Otarama advance reached almost as far as and attained almost the thickness of the Woodstock ice.

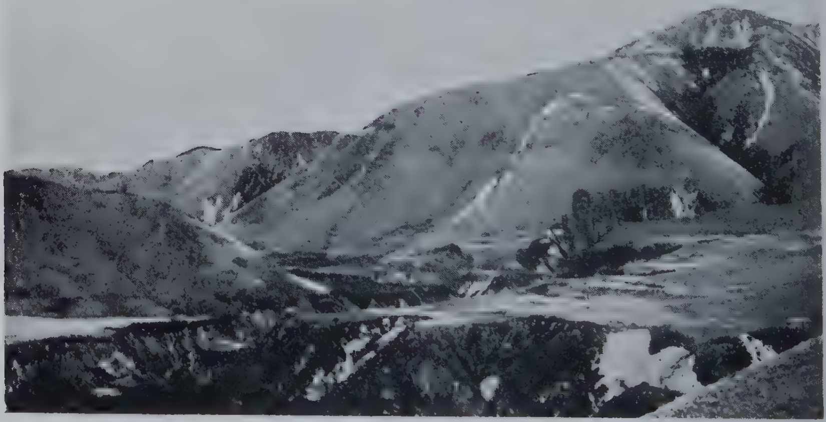

FIG. 8—Upstream end of Staircase gorge of Waimakariri River, showing profile of glaciated trough beneath which the river is now entrenched about 200 ft in a narrow rocky gorge; view south-south-east from 1 mile north-east of Broken River mouth. Staircase Gully mouth and Blackwater terrace remnants right of centre.

Deposits

On the east bank of the Waimakariri River 2½ miles up stream from the lower end of Staircase gorge, the face of a terrace at an altitude of about 1,620 ft exposes a remnant of coarse morainic gravel more than 40 ft thick, including sub-angular to rounded blocks up to 8 ft in diameter, some of which originated in the headwaters region, together with finer rounded greywacke gravel. All pebbles are at least superficially oxidized, and some near the top are thoroughly decayed. The upper surface of the terrace slopes towards the axis of the valley owing to the presence of a soliflual head deposit. It is uncertain whether this deposit is a stranded lateral moraine or a small remnant of a recessional moraine that survived erosion by Otarama ice and meltwater torrents, but it is accordant in height with an extensive terrace 50 ft to 60 ft higher than the Canterbury Plain surface at Woodstock and traceable north-eastwards for several miles. The surface of the Woodstock terrace slopes gently south-eastwards, but it is swampy, probably owing to a capping of poorly drained solifluction products which originated on the hillside at the rear.

Coarse, poorly sorted outwash gravel at least 80 ft thick is exposed in a deep gully near Woodstock homestead, but if it is continuous with similarly yellowed and lightly oxidized gravels near the mouth of Woodstock gully, the total thickness is more than 400 ft. Evidence for continuity is, however, obscured by a deposit of about 200 ft of noticeably fresher Otarama gravels on a bench apparently carved in Woodstock gravels. The lower portion nearer river level, containing more highly rounded material, is interpreted as proglacial outwash laid down in advance of Woodstock ice which later deposited the coarser outwash and moraine above. (A similar but clearer record of ice advance provided by Otarama deposits will be described later.) Other deposits tentatively correlated with Woodstock include the isolated mound, standing about 20 ft above the Canterbury Plain at Springfield, and yellowish gravels underlying Otarama gravels at several places in the Kowai and Little Kowai rivers and also at the lower Waimakariri gorge and Rakaia Gorge.

The Woodstock surface is regarded as a fragment of a former piedmont alluvial plain intermediate in age between the Canterbury Plain and its ancestor in Avoca times. A similar fragment is recognizable south of the Rakaia River, where also it plunges beneath the Canterbury Plain. Speight (1938, pp. 156-7) noted the morainic character of the material underlying the Woodstock surface, but failed to note the weathering which distinguishes it from gravels beneath the Canterbury Plain. He tended to follow Hutton in regarding the Canterbury Plain as due to river planation, and suggested that the Woodstock terrace might be a remnant of the original surface.

Age

The chronological position of the Woodstock advance is deduced from the following evidence: (1) the deposits extend from well below Otarama gravels (which unconformably rest on them) to as much as nearly 100 ft higher; (2) the deposits were laid down in a valley previously eroded hundreds of feet below the floor of the Avoca ice channel; (3) the deposits are more weathered than Otarama gravels, but less deeply or intensely than Avoca deposits; (4) in situation, the deposits belong with those of later advances rather than with Avoca deposits. The Woodstock ice advance is therefore referred to an early sub-stage of the Otiran Glacial Stage.

WOODSTOCK-OTARAMA INTERVAL

Only slight valley-deepening in rock seems to have occurred in response to regime changes accompanying the post-Woodstock deglaciation, though the piedmont alluvial fan was deeply trenched, benched, and dissected. The contrast in weathering, more marked between Woodstock and Otarama than between Otarama and later deposits, results perhaps from mildness of climate rather than long duration of the Woodstock-Otarama interval.

OTARAMA ADVANCE

Name

The last ice advance to reach the lower end of the Staircase gorge is named from "Otarama Stataion" near Kowai Bush.

Ice Extent and Thickness

For reasons to be given later, it appears likely that ice occupied the Staircase gorge only for a short period at the climax of this advance. An upper limit to the thickness of Otarama ice is suggested by uneroded Avoca drift on summits near Avoca and Craigieburn, and by a high-level stranded lateral moraine at the northern end of Trig. I ridge, Craigieburn. In this part of the Waimakariri Valley the ice could not have been much more than 1,000 ft thick. No evidence survives of ice in the central part of Castle Hill Basin, but lower ridges on the fringe of the Avoca Plateau were overridden and the Waimakariri glacier system was connected with the Rakaia for the last time by transfluence through Cass Saddle at the head of Hamilton Creek and Lagoon Saddle at the head of the Harper River. Augmented by large tributaries from the Alpine divide, the trunk glacier filled the entire valley from the northern end of the Craigieburn Range and St. Bernard Range across to Mount Binser and Mount White, submerging all but the summits of Sugarloaf, Trig. I ridge and No Mans Land. The main flow of this and later advances followed the sweeping curves of the main valley, but a large distributary flowed between St. Bernard Range and Broken Hill and thence down lower Broken River valley to rejoin the main stream. At the height of the glaciation transfluence between this distributary and the main stream would have been possible through several gaps.

Deposits

The uppermost terrace at Otarama, near Kowai Bush is underlain by about 200 ft of comparatively fresh sub-rounded to rounded greywacke gravels resting unconformably on an irregular surface eroded from Woodstock gravels and older formations. In this area the upper 20 ft is composed of very coarse unstratified and unsorted morainic gravels, including sub-angular blocks up to 8 ft in diameter, grading laterally into glacifluvial gravels containing isolated large morainic blocks. Good exposures may be seen in Joyce Stream downstream from the railway and in a railway cutting north of Joyce Stream (Figs 9, 10). Younger degradational terraces below the Otarama surface

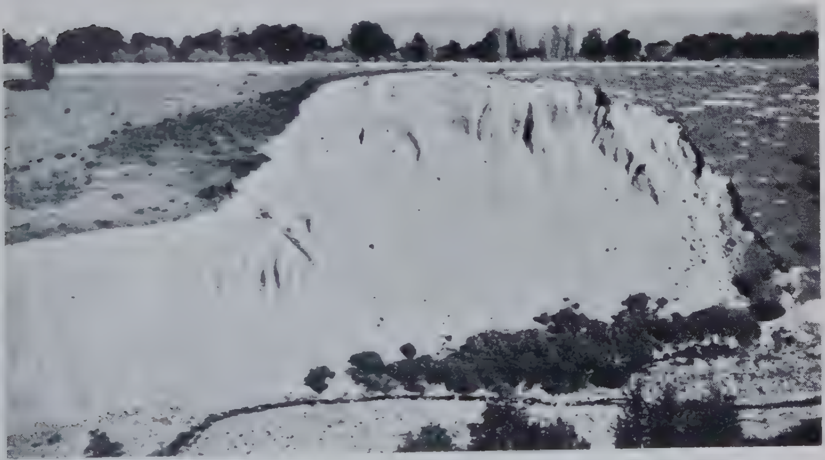

FIG. 9.—Otarama (Canterbury Plain) Surface and underlying glacifluvial gravels, marking climax of Otarama Advance, exposed in Joyce Creek.

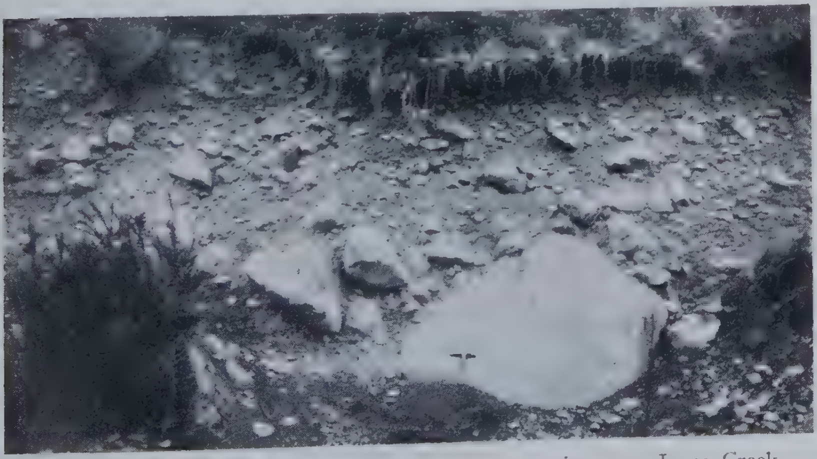

FIG. 10.—Otarama morainic gravels in railway cutting near Joyce Creek.

are littered with large blocks which presumably are a lag-deposit formed during post-Otarama river-planation. Lower parts of the Otarama gravels show better sorting, and have the appearance of proglacial outwash gravels laid down well in advance of the ice.

Downstream from the railway line, Joyce Stream exposes the following discontinuous section:

	(Otarama Surface)	
20 ft	coarse morainic gravel	(right bank)
200 ft	glacifluvial gravel	
	(obscured; interval 10 ft ?)	
25 ft	glacifluvial gravel, grading down to well-rounded, well-sorted fine gravel	(left bank)
	(obscured; probably continued on opposite bank without hiatus)	
20 ft	fine, well rounded and sorted gravel, interfingering below with current-bedded coarse sand (brown-stained)	(right bank)
20 ft	fine laminated grey silty clay	(both banks)
10 ft	laminated silt and clay with peat, interfingering laterally (down-valley) abruptly. with upper part of:	
100+ ft	slightly brown-stained stream-bedded fairly well-sorted gravels	(right bank)

Radiocarbon dating of the peat and a piece of wood also from the silts (Grid. ref. S74/394868, N.Z. Fossil No. S74/525) indicated an age of more than 45,000 years.

If it is assumed that no unconformities are hidden in the breaks noted, the section may record the passage from an interglacial to a glacial climate, and the advance of ice down the valley. The peat and overlying silts were deposited in a lake, which was perhaps impounded against the base of the Torlesse Range owing to rapid aggradation of the axis of the Waimakariri Valley with the arrival of the first floods of outwash gravels in advance of the Otarama glacier. The overlying beds are deltaic, marking the infilling of the lake, which was eventually overwhelmed, and its deposits deeply buried under outwash and moraine. Less probably, in the writer's view, one of the breaks may conceal an unconformity and the lower part of the section may be of Woodstock age, in which case the Otarama beds would not necessarily be as old as indicated by the radiocarbon age of the peat. Further investigation of this critical section is necessary and will require palynological study of the peat layers.

Eastwards from the Kowai Bush area, the upper surface of Otarama gravels becomes the apical portion of the Waimakariri segment of the Canterbury Plain. At Otarama the surface is 1,400 ft above sea-level and 400 ft above present river level. Terrace remnants allow the Otarama surface to be traced up the gorge, diverging progressively from the present river gradient so that the surface is 800 ft above the river a short distance upstream from Broken River junction. Sections in gullies show the gravels beneath the terraces to be coarse and poorly sorted, and they are interpreted as chiefly kame-terrace deposits by lateral meltwater torrents, augmented by deposits from the Esk Valley, which, although itself unglaciated, served as a spillway for meltwater overflowing from Cox Valley through the Lochinvar saddle. The east wall of the upper gorge exposes the following section of deposits filling the deepest part of an ice-eroded gutter beneath a terrace at 2,290 ft above sea-level and approximately 1,000 ft above river level:

80 ft	coarse morainic gravel
200 ft	fairly fine stratified gravel
10 ft	very coarse boulder bed
60 ft	coarse gravel, containing a single 20 ft angular block

Speight (1935, pp. 311-3) described a high terrace in the Esk Valley known as "the tableland" underlain by some hundreds of feet of gravel. This accumulation is due to aggradation by the Esk while blocked by the Waimakariri glacier of the Otarama phase.

Although no Otarama moraines are known in Castle Hill Basin, it is very probable that small valley glaciers and cirque glaciers were present on the flanks of the Craigieburn Range, since the small moraines in this area described by Speight (1935, pp. 307-9) were probably formed during the less intense Blackwater glaciation. Poorly exposed gravel cappings on the "Long Spur" east of Thomas River and on another spur east of Broken River, judged from their heights, can only be of Otarama or Woodstock age.

Duration

Considering that a great part of the Waimakariri segment of the Canterbury Plain was constructed at this time, the Otarama advance seems to deserve the status of a glacial substage. The quantity of moraine surviving at Otarama is small, suggesting that the Waimakariri glacier did not extend this far for very long, but the great spread of outwash gravels associated with it, up to 200 ft thick at Otarama and Woodstock, requires that the discharge of glacial debris by meltwater torrents continued for a considerable period.

POST-OTARAMA RECESSION

With the retreat of ice from the Otarama maximum, the deposits from this advance were eroded and reduced almost to their present extent. The deep, narrow and rocky upper gorge was incised at this stage to a level several hundred feet lower than the irregular floor of the main glacier channel along the base of the Puketeraki Range, and to within 150 or 200 ft of the present gorge floor level. Superposition through Otarama glacial deposits probably explains the distribution of terrace remnants and gravel-filled gutters at intervals along both sides of the gorge, which give the impression that the river gorge is off the axis of the Otarama ice trough in places. Otarama deposits are not appreciably more weathered than deposits of the Blackwater advances, indicating that the gorge-cutting was rapid, anad effected during a relatively cool climate unfavourable for rock decay.

BLACKWATER ADVANCES

Name

The name is derived from Lake Blackwater which lies amidst extensive moraines and outwash.

Ice Extent and Thickness

The Blackwater deposits record two distinct advances (Blackwater I, II) separated by a brief recession and followed by intermittent withdrawal interrupted by one or two temporary re-advances. Clear evidence for irregular decline from earlier glaciations has not survived, but it is very likely that such evidence would be destroyed by subsequent advances. Ice streams of the Blackwater advances completely filled the upper reaches of the Waimakariri trough and the main tributaries entering from the north, leaving glacial sculpture fresher than that in the Staircase gorge, which has not been glaciated since the Otarama advance. A diffluent tributary crossed Goldney Saddle and flowed through Cass Basin, making marginal contact with the trunk glacier south of Sugarloaf. The main stream of this distributary remained distinct from the trunk glacier and continued beyond the Cass Basin as the Lake Pearson-Winding Creek lobe. At the same time a separate distributary followed the Slovens Creek channel, divided from the trunk glacier by the Gog-Magog ridge and the Trig. I ridge east of Craigieburn. The separation was not complete, however, since interflow between the main stream and the distributaries occurred through saddles, for example those near Trig. A, Craigieburn, and north of the St. Bernard Range. At the height of the earlier Blackwater maximum the Winding Creek and Slovens Creek lobes rejoined south of the St. Bernard Range, and thrust beyond so that No Mans Land ridge was half encircled by ice. At the same time the ice was thick enough for the Winding Creek lobe to deposit moraine at the Craigieburn Saddle and to discharge a vigorous lateral meltwater stream into Castle Hill Basin. Small moraines in the upper reaches of Broken River and its tributaries and Craigieburn River (Speight, 1935, pp. 307-9) indicate the limited extent of glaciation within Castle Hill Basin. The Waimakariri trunk glacier reached the base of the Puketeraki Range near the entrance to the upper gorge, and deflected ice issuing from the Poulter Valley so that it almost overrode low ridges between Mount White Station and the lower Esk Valley.

After a temporary recession the Winding Creek and Slovens Creek lobes re-advanced to the northern base of No Mans Land, combining to build a medial moraine near Vagabonds Inn tarn. The trunk glacier meanwhile re-advanced at least to the northern end of the Lake Blackwater terrace.

Deposits

The most important areas of Blackwater glacial deposits are: (1) a broad terrace on the south bank of the Waimakariri River (Fig. 11), extending from opposite the mouth of the Poulter River to the eastern base of Mount Rosa, covering about 7 square miles; and (2) moraines south-east of Mount St. Bernard connecting with extensive outwash deposits in Slovens Creek, Winding Creek, and Broken River, and correlated with terrace remnants in Staircase gorge, totalling about 10 square miles. The surface of the former (Lake Blackwater Surface) ranges in altitude between 2,250 ft (i.e., 800 ft above river level) at the western end, and about 2,000 ft (700 ft above river level). Gullies dissecting the north-eastern margin show that the surface is underlain by comparatively fresh grey gravels that vary in texture and thickness but generally show the poor sorting and rough stratification of ablation moraine and outwash gravels. Large morainic blocks are rare, and the Blackwater deposits on the whole are finer than those of previous advances. Deeper gullies show that the base of the Blackwater gravels descends to within about 150 ft of present river level.

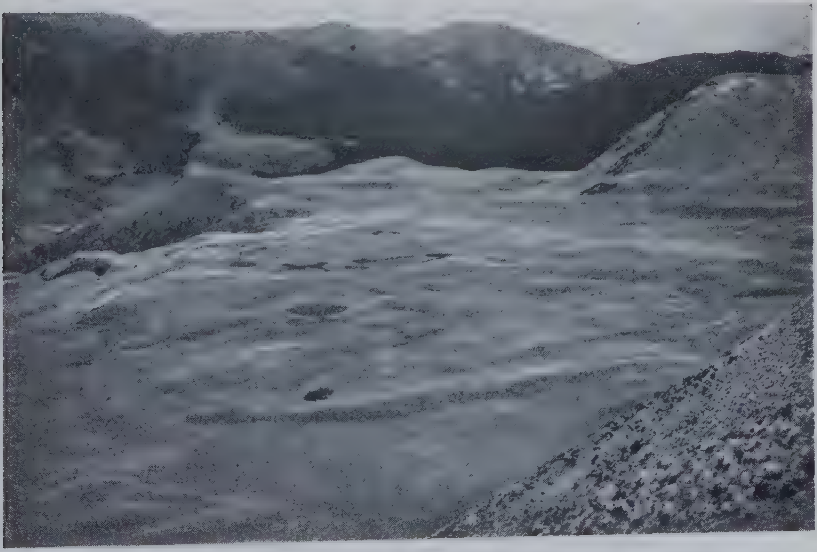

FIG. 11.—Southern portion of Lake Blackwater terrace, viewed from eastern slopes of Trig. I Hill, showing irregular morainic surface, kettle-holes, and tarns. Bush-covered spur of Puketeraki Range lies beyond the 800 ft-deep upper gorge of the Waimakariri River, which passes to the right behind Mount Rosa.

Moraine dumped during the final wasting phase is heaped in undulating mounds and ridges over much of the Lake Blackwater Surface, arranged in places into series of low arcuate ridges, which are scarcely discernible on the ground and seen only with difficulty in stereo-pairs of air photographs. Lake Blackwater is the largest of many tarns and swampy kettle-holes dimpling the surface of moraine and outwash.

The two maxima and subsequent recessional phases are more clearly differentiated in the distributary lobes than in the main valley, perhaps because diffluent ice-streams were nourished chiefly through diversion of upper layers of the trunk glacier over spillways, and were thus very sensitive to fluctuations in the thickness of the trunk glacier. Consequently, distributary lobes suffered greater climatic oscillations. Moraines and outwash in lower Slovens Creek and Broken River clearly show two distinct maxima, which are distinguishable in terrace remnants down-valley to beyond Staircase (Figs 12, 13). A higher terrace near Avoca is a remnant of the "Chimney Surface", named after a group of derelict brick chimneys at the site of a former mining camp. From a medial moraine at the foot of Mount St. Bernard (No. 1. Moraine of Speight, 1938, p. 149; 2,350 ft), the Chimney Surface may be followed as extensive terrace remnants around both flanks of No Mans Land and down the lower Broken River and Staircase gorges to a point opposite Staircase railway station at 1,490 ft. Farther down the valley it becomes difficult to distinguish fragments of the Chimney Surface from the Vagabond Surface and from river-planed benches.

The second Blackwater maximum is even more clearly marked by ice-contact surfaces and a peripheral meltwater channel below No. 1 Moraine at Winding Creek, and by a broad arcuate belt of low-terminal moraine mounds near Vagabonds Inn tarn at about 2,050 ft above sea-level, which is continued to the east across Slovens Creek at the same altitude. A smooth outwash plain (named "Vagabond Surface") about 100 ft lower than the Chimney Surface, extended southwards from these terminal moraines and is distinguishable also as terrace remnants down the gorges to beyond Staircase. An accordant system of terraces may be followed down Winding Creek and Broken River from Speight's "No. 2 Moraine", which was essentially a medial moraine between the Winding Creek and Slovens Creek lobes. It is significant that the profiles of these terraces are distinctly lower than Otarama terraces and the Canterbury Plain, which is thus older than the Blackwater advances.

The Chimney Surface at Avoca (Fig. 14) is underlain by about 200 ft of moraine and moderately fine outwash, whereas the Vagabond Surface is underlain by 220 ft of unusually fine and well sorted outwash gravel for a situation so close to the terminal moraine of the glacier. Outwash from the ice tongue issuing from the Poulter Valley discharged into the lower Esk Valley, causing aggradation estimated at about 250 ft, which built up a surface accordant with the moraines and outwash from the Waimakariri trunk glacier. Another accordant surface extends from the Esk Valley up the tributary Nigger Stream, and probably

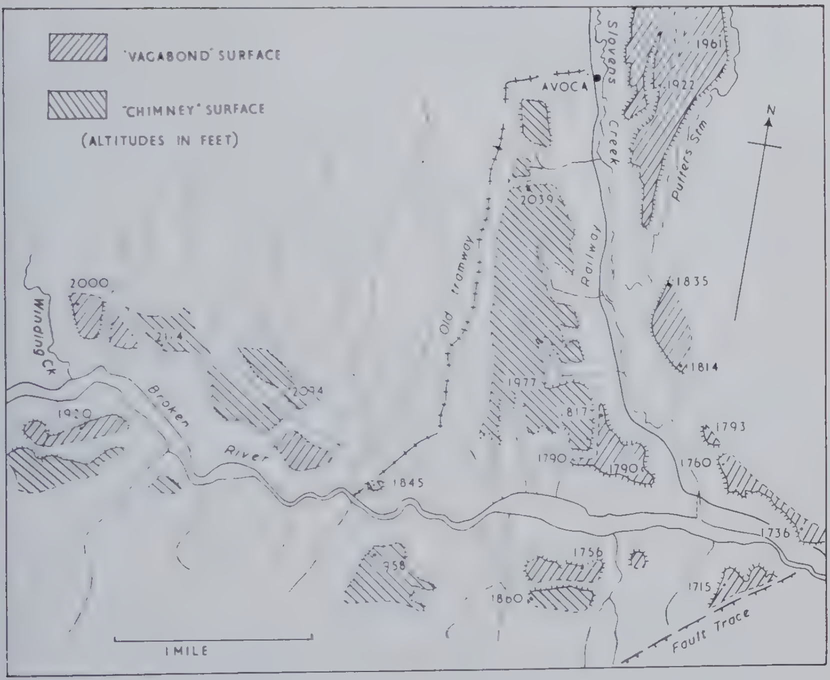

FIG. 12.—Map of Blackwater outwash surfaces near Avoca.

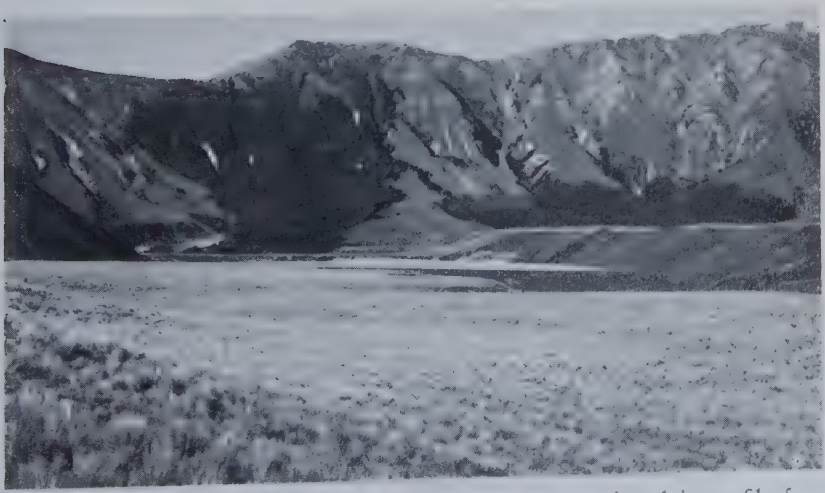

FIG. 13.—Vagabond (left) and Chimney (right) surfaces viewed in profile from near Avoca, looking south across Broken River towards Torlesse Range.

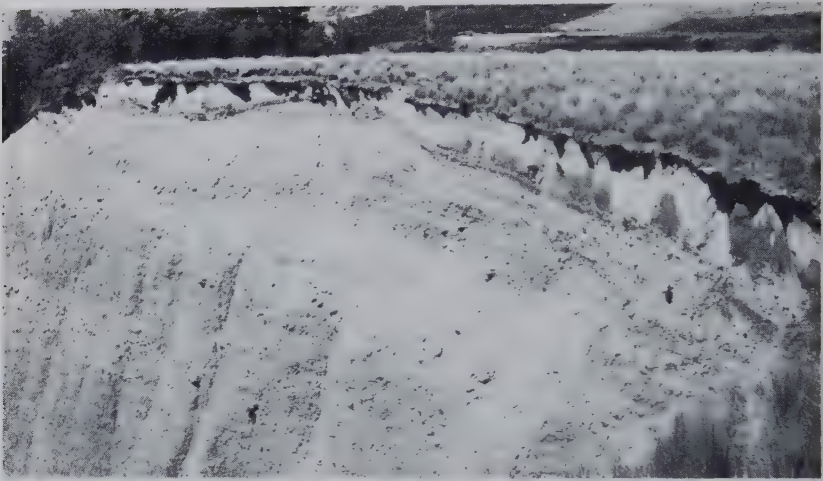

Fig. 14.—Upper portion of Blackwater–I glacifluvial gravels capped by 2-4 ft of loess at southern extremity of Chimney terrace, Avoca.

links with the Lochinvar moraine field (Speight, 1938, p. 145) situated in a spillway through which meltwater from the Cox tributary of the Poulter glacier overflowed into the Esk catchment.

Two phases of aggradation separated by a period of downcutting and planation are indicated by terraces in Broken River and its branches in Castle Hill Basin, but until these terraces are studied in detail it is impossible to correlate them individually with the Winding Creek-Slovens Creek surfaces. From their heights, however, the built-up surfaces can be assigned to the Blackwater glaciation, when lateral meltwater torrents overflowed the Craigieburn Saddle and augmented the outwash from small glaciers and debris from frost-riven slopes on the Craigieburn Range.

Speight (1938, p. 149) mapped and described a group of concentric moraine ridges and outwash channels in Winding Creek marking fluctuations that preceded the end of the Blackwater glaciation (Fig. 15). Scattered moraine mounds near Flock Hill homestead indicate minor re-advances, and a stranded medial moraine north of Trig. I near Lake Grasmere is also referred to the post-Blackwater declining phase.

Duration

In contrast to those of earlier ice advances, the original surfaces of Blackwater deposits survive extensively, although the finer details of surface form have been obliterated by subsequent frost action and by weathering and oxidation to depths up to 3 or 4 ft; only the largest moraine blocks protrude above the surface. Blackwater I and Blackwater II deposits do not differ perceptibly in weathering, yet the intervening recession was of sufficient duration for 100 ft of downcutting in gravels and for partial destruction of the Chimney Surface by stream planation before re-advancing ice produced the Vagabonds Inn moraine and outwash plain. It is uncertain whether the varved silts of Winding Creek (Speight, 1938, p. 150) were deposited during this interval, or during a later fluctuation. It is difficult to avoid the conclusion that the duration of the collective Blackwater advances was of substage magnitude.

POST-BLACKWATER RECESSION

There is evidence that proglacial lakes formed as the Blackwater ice wasted and retreated, and that meltwater floods rapidly trenched the moraine and outwash dams and lowered the lakes. The upper gorge of the Waimakariri River was deepened to about its present depth at this stage while Broken River and Slovens Creek cut their inner gorges through Blackwater drift and as much as about 100 ft into pre-Pleistocene rocks below the floor of the Blackwater channels. Products of the succeeding Poulter ice advance are so slightly weathered that most of the weathering of Blackwater deposits can be attributed to mild conditions in the interval, which is therefore assigned the status of an interglacial substage though shorter than the post-Otarama interval.

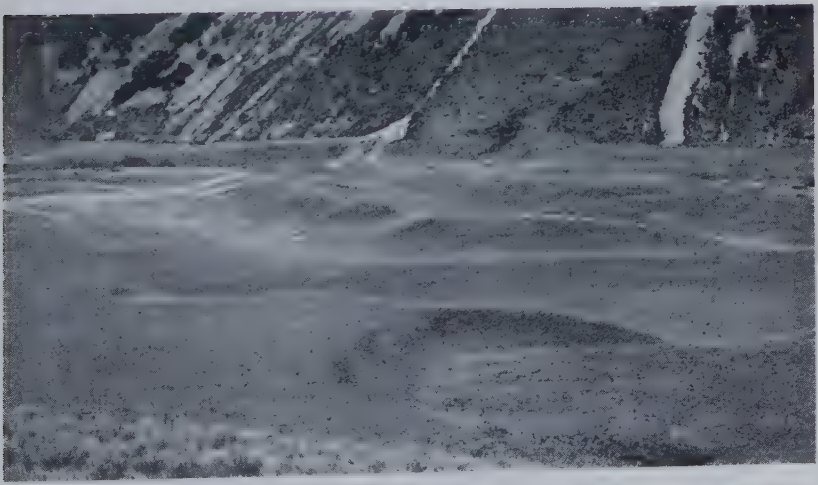

FIG. 15.—Innermost moraine loop of concentric series in Winding Creek (post-Blackwater recessional phase).

POULTER ADVANCE

Name

The name Poulter Advance is given to the final major ice-advance, which deposited impressive mounds of terminal moraine in the main Waimakariri Valley near the mouth of Poulter River.

Ice Extent and Thickness

The Waimakariri glacier was joined by tributaries from the White, Crow, Bealey, Hawdon, and Andrews valleys, and at its maximum, from the Poulter Valley. The trunk glacier snout thrust forward almost to the mouth of Esk River, but there followed stagnation of the lower three miles of the glacier while the Poulter glacier shrank until it no longer joined the Waimakariri glacier. A distributary probably entered Cass Basin through Goldney Saddle at the maximum advance, but its snout certainly did not reach beyond Lake Grasmere. The ice surface in the main channel rose high enough to discharge surface and lateral meltwater through St. Bernard Saddle (2,030 ft) into the head of Slovens Creek. As the depth of recent gravel underlying nearby parts of the Waimakariri River bed is unknown, the full thickness of ice is uncertain, but it was more than 500 ft opposite St. Bernard Saddle. Freshly ice-abraded rock surfaces indicate that the upper trough valley upstream from Crow River was filled with well over 1,000 ft of ice.

Deposits

Poulter glacial deposits are distinguished by freshness, survival of small-scale constructional surface details, and their occurrence down to and below present river level. Moraine and outwash occur chiefly in the Waimakariri Valley in the vicinity of the Poulter junction and between the Poulter and Esk rivers north-eastwards from Whale Hill to the foot of Mount White. A small area of moraine and outwash occupies the southern part of Cass Basin and a few other moraine remnants are known.

Mounds of end moraine on both banks of the Waimakariri River upstream from the Poulter River mouth cover several hundred acres and extend vertically from river level through about 400 ft up to an altitude of about 1,900 ft (Fig. 16). Resting on a bedrock sill marking the downstream limit of the overdeepened trough, the lower part of this accumulation includes till and silts deposited in proglacial lakes during recession from the early Poulter maximum stage, covered by till and end moraine due to the re-advance which almost reached the Poulter Valley mouth. The uneven eastern face of this younger end moraine has the character of an ice-contact surface. Kame terraces along the inner trough walls as far downstream as the lower end moraine present similar surfaces towards the axis of the valley. Stagnant ice, protected by deep supraglacial debris, apparently had not melted when re-advancing ice overrode it and built the higher Poulter

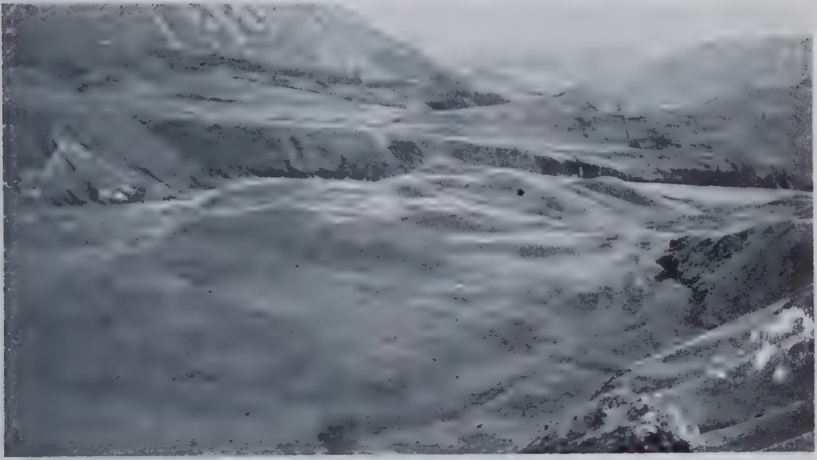

FIG. 10.—Crest of Poulter end moraine in Waimakariri Valley 1 mile upstream from mouth of Poulter River. Slopes of moraine faintly terraced by beaches marking stages in lowering of Glacial Lake Speight.

end moraine. Meltwater from the snout flowed down-valley, partly on buried stagnant ice and partly on benches eroded from the valley wall, giving rise to the kame terrace gravels which rest on marginal lake silts and till. A steep outwash fan from high moraine mounds north of the Waimakariri River slope towards the mouth of the Poulter River where it may have accumulated against the Poulter glacier. Melting of the stagnant ice released quantities of moraine, some of which survives on low terraces from 10 to 20 ft above the river as an ablation deposit ridged by crevasse-fillings. Kame terraces north of the river upstream from the high end moraine are largely buried under post-glacial shingle fans. Poulter outwash is far less abundant than that from earlier known advances, and in the main valley it is not recognized beyond the entrance to the upper gorge.

A medial moraine built out from the base of Sugarloaf during the Blackwater advances was enlarged by the addition of lateral moraine from a westward bulge of the trunk glacier, which at the same time deposited a moraine on St. Bernard Saddle from which striated stones have been obtained (Gudex, 1909). A lateral meltwater torrent flowed down Slovens Creek and deposited outwash gravels that now form the floor of the valley as far down as Craigieburn. Post-glacial shingle fans almost obscure the Lake Grasmere end moraine and its small valley train which passes beneath Lake Pearson. Thin till of Poulter age is exposed in roadside cuts between Goldney Saddle and Bealey.

Duration

A rapid ice advance of short duration could account for the meagre extent of deposits from the early Poulter maximum. Furthemore, the succeeding recession lasted no longer than the likely persistence of moraine-buried ice—perhaps only a few hundred years—and the final advance, although marked by more extensive deposits, was insignificant in its effects compared with recorded pre-Poulter advances. Blackwater deposits were not seriously threatened by erosion or burial during the Poulter advances, which together amounted to a glaciation of smaller magnitude than either of the Blackwater advances.

POST-POULTER EVENTS

The short duration of post-Poulter time is indicated by immature weathering profiles shown for example in railway cuttings near Lake Sarah where Poulter deposits are unoxidized and leached only to a depth of two or three feet. Solifluction effects are at a minimum, and Poulter surfaces everywhere are characterized by protruding boulders and general lack of erosional defacement of original detail. Fine striations may still be found on ice-shorn rock surfaces.

Minor Late Advances

Small moraines are present in the upper reaches of the Waimakariri River and its branches (e.g., Bealey and Hawdon valleys; Speight, 1938, p. 153) and in basins at the heads of Craigieburn and Broken rivers, but it is evident that no major ice advance has occurred since the Poulter second maximum.

"Glacial Lake Speight"

There is evidence that the second Poulter advance was followed by a sudden decline in glacier nourishment and a rapid rise in temperature. Wastage of the Waimakariri glacier affected its whole length except near the snout where it was probably protected by supraglacial rock debris. Beach ridges and small deltas show that a lake was impounded temporarily behind the end moraine, extending up the valley at least ten miles to the north of the Hawdon River, where beaches disappear beneath the Hawdon fan and the recently aggraded main valley floor. It is convenient to follow American practice and assign names to the more important former lakes. "Glacial Lake Speight" is proposed for the above post-Poulter lake, which reached a maximum level 1,550 ft above sea-level. Intermittent lowering is indicated by flights of beaches, deltas, and faint wave-cut nicks at varying intervals on both walls of the Waimakariri Valley. Beach ridges are larger at the eastern than at the western end of the lake, suggesting that the prevailing winds of the time were westerly. A delta built up the Andrews River is complex owing to changes in water level during its growth. Undulating ablation moraine immediately up-valley from the north end of the high end moraine shows no trace of lake shorelines, from which it is inferred that stagnant ice continued to occupy this situation even during the early stages of draining of the lake. Rapid though intermittent fall of lake level is satisfactorily explained if it is assumed that the dam was partly composed of debris-covered stagnant ice, which would have been subject to successive sudden collapses during melting. It is noted in this connection that moraine dams can be stable and permanent structures, as shown for example by the survival of lakes Ohau and Pukaki behind moraine dams probably equivalent to Poulter in age. Draining of Glacial Lake Speight at least down to the level of the present riverbed was accomplished before the final melting of buried early-Poulter ice farther down the valley, for otherwise the ablation moraine east of the high end moraine could not have escaped destruction.

The above evidence points to rather brief existence for Glacial Lake Speight, yet the interval between the disappearance of the unprotected glacier trunk and the beginning of lake-draining was long enough for the construction of two immense alluvial fans on the lower southern slopes of Mount Binser, the larger being more than 2 miles wide at the base. Both fans were built to their present height during the highest stage of Glacial Lake Speight, and the more easterly fan shows ice-contact features on its eastern side, which must therefore have accumulated against the stagnant ice west of the high end moraine. During halts in the lowering of lake level, wave action scored terraces along the fore-set face of the eastern fan, and also of a small lower fan built at the mouth of a trench incised below the upper fan surface. It is not unreasonable to think of Glacial Lake Speight co-existing with buried ice for hundreds of years before lowering commenced.

Alluvial cones and fans are conspicuous in the Waimakariri no less than in other Souh Island alpine valleys. Some, from their situation, must have been constructed entirely since the end of the Poulter glaciation, but the majority more probably have a history, beginning earlier in the Otiran Glacial Stage, of periods of growth alternating with dissection or truncation by streams. Many are known to have received substantial additions during the past hundred years. The relation of the Mount Binser fans described above to Glacial Lake Speight thus fixes the date of their main period of formation with unusual precision. Fan building undoubtedly was proceeding in periglacial situations during the Poulter ice advance, and spreading into deglaciated areas as shrinking glaciers exposed oversteepened slopes to attack by frost. Conditions would have been less favourable for slope-grading and fan building during the post-glacial Climatic Optimum when the vegetation cover was probably more extensive than now, but revived erosion and fan-building would have accompanied post-glacial minor climate deteriorations as in the past five hundred years.

Other Glacial Lakes

Glacial processes are responsible more or less directly for the origin of most of the lakes within the Waimakariri watershed and for countless small ponds and tarns.

EXISTING LAKES

The existing lakes have been caused by one or more of the following happenings: (a) glacial overdeepening of valley floor; (b) blockage of formerly glaciated valleys by proglacial moraine and outwash deposits; (c) blockage of drainage by post-glacial alluvial fans; (d) landslides fundamentally due to glacially oversteepened slope of trough walls; (e) rise of ground-water level above the floors of kettle-holes in moraine and outwash valley train surfaces. To give examples, lakes Hawdon and Letitia are essentially rock-impounded; Grasmere may have formed originally behind a moraine loop, and is perhaps greatly reduced in area by the growth of a large fan from Ribbonwood Creek; Pearson and Sarah are dammed by fans. Lakes Marymere and Blackwater, and Vagabonds Inn tarn are the largest of many water-filled kettle-holes. The origin of Lake Minchin near the head of the Poulter Valley has been ascribed to landslides promoted by seismic shocks (Speight, 1933, p. 179).

FORMER LAKES

The existence of former lakes (Fig. 17) is indicated by beach and delta deposits recognizable from both surface form and sedimentary characters, and by varve silts where no morphologic evidence survives. Glacial Lake Speight has been described above. Next in order of magnitude was Glacial Lake Cass, which occupied the Cass Basin from Goldney Saddle to the Grasmere moraine up to a level of about 1,970 ft, (i.e., a little higher than Lake Speight). Lake Cass formed when the surface of the trunk glacier dropped sufficiently to starve the Goldney Saddle distributary so that ice disappeared from Cass Basin. Ice apparently did not re-occupy Cass Basin during the second Poulter advance, but the trunk glacier surface controlled the level of Lake Cass, as indicated by the height and distribution of lake beach deposits near the mouth of Cass River. The post-glacial fan of Cass River may not have been built out into Cass Basin soon enough to prevent draining of Lake Cass

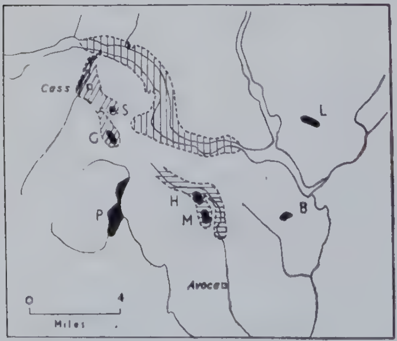

FIG. 17.—Map showing location of existing lakes, and location and approximate extent of former glacial lakes. (B = Blackwater; G = Grasmere; H = Hawdon; L = Letitia; M = Marymere; P = Pearson; S = Sarah. Vertical ruling: Glacial Lake Speight; horizontal ruling; Glacial Lake Craigieburn; diagonal ruling: Glacial Lake Cass; solid black: existing lakes.)

when the Waimakariri glacier disappeared, and it is therefore doubtful whether Lake Grasmere is a shrunken remnant of Glacial Lake Cass, or whether Lake Cass was first drained by river down-cutting of the rock bar at Goldney Saddle, and Lake Grasmere formed subsequently through obstruction of north-flowing drainage by the Cass River fan.

Lake Hawdon is undoubtedly a remnant of a proglacial lake that temporarily filled Slovens Creek Valley in the vicinity of Craigieburn as ice receded from the Blackwater–II maximum. Lake Hawdon is now bounded to the north by a Poulter Valley train surface leading up to St. Bernard Saddle, but bedrock in the bed of Slovens Creek shows that the valley has never been incised deeply enough to drain completely the remains of Glacial Lake Craigieburn.

Proglacial lakes have occupied Winding Creek on at least two occasions. Most recently, the innermost moraine arc of the series at the foot of No Mans Land dammed a small lake during the final post-Blackwater ice recession, as is shown by the presence of small lake-shore terraces on the lower slopes of the moraine. Varve silts underlying late Blackwater till and outwash gravel (Speight, 1938, pp. 150-1) were undoubtedly deposited in a proglacial lake during a recession of ice, perhaps after the Blackwater–I maximum. Deposits marking several other proglacial or ice-margin lakes are also known. Lakes may have formed in the lower Esk Valley whenever its outlet was blocked by ice or by vigorous aggradation in the main valley, but the writer's incomplete knowledge of the Esk suggests that aggradation by the tributary generally kept pace with changes in the main valley, and that if lakes ever formed, their existence was brief (compare Speight, 1938, p. 313).

Existing Glaciers

Permanent ice in the Waimakariri watershed is now confined to thin glacierets in the upper reaches (Fig. 7). Except for the Crow Glacier on Mount Rolleston and a small glacier in the head of White River, these are no more than small perched ice-fields on alpine shoulders above the glaciated troughs.

ISOLATION FROM SEA-LEVEL CHANGES

The profiles and gradients of streams discharging glacial outwash from the Waimakariri catchment are now fairly well known, but information is far less complete regarding the gradients of interglacial times. Moreover, coastal evidence in Canterbury for late Pleistocene relative changes of level of land and sea is in need of reconsideration in the light of advances in glacial chronology. It would therefore be premature at this stage to attempt the correlation of Waimakariri gradients with sea-level fluctuations. The available information is insufficient to indicate the relative heights of sea-level and positions of the coastline when the successive piedmont alluvial plains were growing. The gradients of inland surfaces with which this paper is concerned appear to be explained adequately by changes in the regime factors (discharge, quantity, and character of load, chiefly) in response to climatic fluctuations superimposed upon a progressive lowering of general base-levels, and the hingeline separating climatic from thalassostatic surfaces appears to lie to the east of the mountain front.

ACKNOWLEDGEMENTS

The Lands and Survey Department at Christchurch contributed substantially towards the base map by making available plots of aerially-photographed strips along the Christchurch-Greymouth Railway and the Arthurs Pass main highway, and by supplying the data necessary for re-expressing trigonometrical co-ordinates in terms of the National 1,000 yard grid. The New Zealand Railways Engineers Branch at Christchurch provided altitude data along the Christchurch-Greymouth Railway. The author is particularly indebted to Professor J. Calder of Canterbury Agricultural College and to Mr. G. Urquhart of Flock Hill Station for permission to use cottages at Avoca as field headquarters. Much valuable criticism and encouragement has been given by others interested in Pleistocene geology, especially Dr C. A. M. King, Dr R. P. Goldthwait, Messrs R. P. Suggate, B. W. Collins, J. P. Fox, and J. D. Campbell, each of whom joined in field trips. Dr W. H. Harris kindly made preliminary pollen studies on the fossil peats, and the Director of the New Zealand Geological Survey arranged for radiocarbon dating of peat and wood samples. Finally, grateful acknowledgement is made to the Royal Society of New Zealand for a grant from the Hutton Research Fund towards field and photographic expenses.

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A GAMMA RADIOACTIVITY SURVEY OF SOME OF THE GEOTHERMAL AREAS OF THE NORTH ISLAND OF NEW ZEALAND

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(Received for publication, 22 July 1957)

Summary

In a preliminary survey of gamma radioactivity of some geothermal areas in the North Island of New Zealand a wide variation in the radioactivities of soils, pools, and sinters was found between separate thermal areas, particularly between sulphate and chloride areas. In the Waiora area, the average radioactivity of hot pools with no overflow was greater than that for hot springs.

In some hot pools, the variation of gamma radioactivity with depth showed the presence of comparatively active ledges. Sinter deposits around these pools were more radioactive than nearby soils.

It is concluded that the radioactivity observed in the pools is controlled by the physical and chemical characteristics of the pools and not by the water entering from depth.

INTRODUCTION

Radioactivity measurements in New Zealand have in the past been confined mainly to prospecting with equipment capable of detecting gamma rays (McCahon, 1946), and to a few determinations made 30 years or more ago (Maclaurin and Wright, 1911; Rogers, 1926; Grigg and Rogers, 1929) of radon concentrations of some thermally active pools in the Taupo area. Some work has been done elsewhere, in particular in the thermal areas of Japan (Kuroda, 1949; Kuroda and Yokoyama, 1949) and in Italy (Straniero, 1951, 1952).

In connection with the search for geothermal steam, a preliminary investigation was carried out in the North Island thermal areas by measuring the radioactivity of pools, siliceous sinters, and soils, with counting equipment capable of high statistical accuracy.

PROGRAMME

During the period 1952 to 1955, measurements were made of the intensity of gamma radiation:

(1) In selected pools in each of the areas shown in Table 1.

(2) Of soils within an area, for comparison with other areas and for a reference to which pool activities could be related.

(3) In relation to depth in some pools selected from (1).

EQUIPMENT

The programme above was carried out using a single Geiger tube, the pulses from which were made to actuate a mechanical register with the resolving time of 0·02 sec. The count rate was scaled down four times when necessary, which increased the permissible counting rate, with only a few per cent. loss, to 3,000 pulses/min (Blackman and Michiels, 1948). The extra-high-voltage supply was obtained from a pack of 30-volt hearing-aid batteries.

The Geiger tube consisted of copper, 1 in. in diameter and 18 in. long, and was very robust. It was filled with argon and alcohol at partial pressures of 9 cm and 1 cm of Hg respectively. The anode end of the tube and the pre-amplifier were protected by a coaxial waterproof housing. The whole assembly was fairly shock-resistant. The probe and counting apparatus were connected by a watertight cable 25 ft long. The components of the probe and cable were carefully selected, and tests showed that temperature changes within the range 5° and 150°C had no effect on the operation of the equipment.

A boom was constructed for lowering and raising the probe, for the measurement of count rates at various depths in the pool.

EXPERIMENTAL

The probe was lowered, without the aid of the boom, into selected pools until it lay horizontally on the bottom, and its depth was noted. It was also laid on soil and/or sinter on the edge of many pools. Each count rate was corrected for the cosmic ray contribution which had been measured at various depths by lowering the Geiger tube horizontally into Lake Taupo. The count rate in the lake decreased with depth, as was expected (Wilson, 1952), as the contribution from the water in the lake is negligible.

The count rate thus measured in a pool comprises contributions from the water and from the material lining the pool.

In four pools of the Waiora thermal area, the radioactivity was measured at various depths. These particular pools were selected because the probe, when laid on the sinter around them, or placed in the pool itself, registered a higher count rate than when laid on the soil near them. For these experiments, the probe, in a vertical position, was lowered with the aid of the boom. The depth of the probe was considered to be zero when the Geiger tube was just submerged.

RESULTS

Table 1 gives the average count rates obtained in various thermal areas with the Geiger tube lying in pools and on sinters or soils at the edges of pools.

TABLE 1.—Average Counting Rate in Pools, on Sinters, and on Soils.

Region	*Pools pulses/ min	No. of pools	Sinter pulses/ min	No. of sinters	Soil pulses/ min	No. of soil determinations
D-Line					118	8
Wairakei	170	10	130	4	110	6
Waiora	196	21	830	14	113	16
	†128	7				
N-Line	274	3			102	2
Huka	109	2			92	2
Spa	126	12	74	1	123	17
Rotokaua	86	26	92	2	83	9
OrakeiKorako	39	4	38	9	67	3
Tikitere	131	12			116	1
Tarawera	130	1			212	1
Ketetahi	99	2			129	1

*Pools where sinter biases the results are not included. These figures include the contribution from the lining of the pool, as well as that from the water.
†Average of springs only—stagnant pools excluded.

Table 2 gives a selection of the results from some of the more interesting areas—namely, Waiora (Fig. 1), Wairakei (Fig. 2), N-Line, Spa, and Karapiti, showing the large variations of count rate that were observed.

The count rates at various depths in pools 418, 419, 427, and 472 have been plotted in Fig. 3.

All results in Tables 1 and 2 and Fig. 3 have been corrected for cosmic ray contribution. The standard deviation of the individual count rate was about 10%.

DISCUSSION

Pools

There are greater variations among the pools in the Waiora area than in other areas. In general, the pools that exhibited higher activities than normal were stagnant—i.e., they had no water overflow. The high radioactivity of the springs 418, 419, and 472 was mostly due to the active sinter deposits. The stagnant pools 443a, c, and d (see Figs 1 and 2) have a similar appearance and pH, but give very different count rates (443a gave 505 c/m, and 443d gave 120 c/m). Wide variations such as these were also observed by Kuroda (1944), who found small insignificant springs exhibiting high radioactivity.

Except for pools along N-line, at Waiora, and Wairakei, and pool 34 at the Spa, gamma radioactivity in pools is low, comparable with that of the soils, and relatively constant. This suggests that the high counting rate recorded in some pools is attributable to the lining of the

TABLE 2.—The Counting Rates of Selected Pools, and of Sinters and Soils Associated with these Pools. The Results Obtained for Karapiti Fumarole are also included.

Area	Description of pool or place	Counts/min of Geiger tube			*pH	*Temp °C
		in sinter	on soil	in pool		
Waiora	403		59	134	2·8	47
	414		123	254	2·9	75
	418 ⎫ Heavenly		135	328†	2·3	81
	419 ⎭ Twins	650		176†	2·3	82
	6 ft downstream 419	1691				
	15 ft downstream 419	1921				
	60 ft downstream 419	287				
	427		158	246†	2·4	49
	430			427	2·5	54
	443a		130	505	2·5	82
	443c			159		
	443d			120		
	472 (Emerald pool)	1773		600†	2·5	67
	5 ft downstream 472	977				
	15 ft downstream 472	1385				
	30 ft downstream 472	567				
	477		134	274	2·7	74
	498	247	82		2·6	58
Wairakei	113 (Opal Pool)	118‡	132	167	6·0	87
	198		122	166	6·2	99
	200 (Bridal Veil)	127			7·3	60
	205 (Devil's Heel)			244	8·0	100
N-Line	681		88	281	2·7	95
	688			348	—	—
	690			193	2·8	87
Spa	34 (Satan's Glory)			155	3·0	83
	35		89	115	7·8	50
	39 (Satan's Laundry)			95	6·9	88
	Steaming bank behind 39		152			
	51 (Witch's Cauldron)	74	45	76	7·8	84
	56 Paddle Wheel Geyser		74	75	8·0	88
	76			53	—	—
	Inside steam vent near 76		95			
	Steaming ground near 76		308			
Karapiti (712)	30 ft from fumarole		110			114
	Rocky edge of fumarole		291			
	2 ft inside fumarole Geiger tube vertical		1024			

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*Supplied by Mr D. Gregg, of Geological Survey, Rotorua, New Zealand.

†The count rate given here is the average of the count rates measured at intervals as the tube was lowered into the pool.

‡The Geiger tube in this case was placed in the overflow channel which contained a soft deposit and was not sinter.

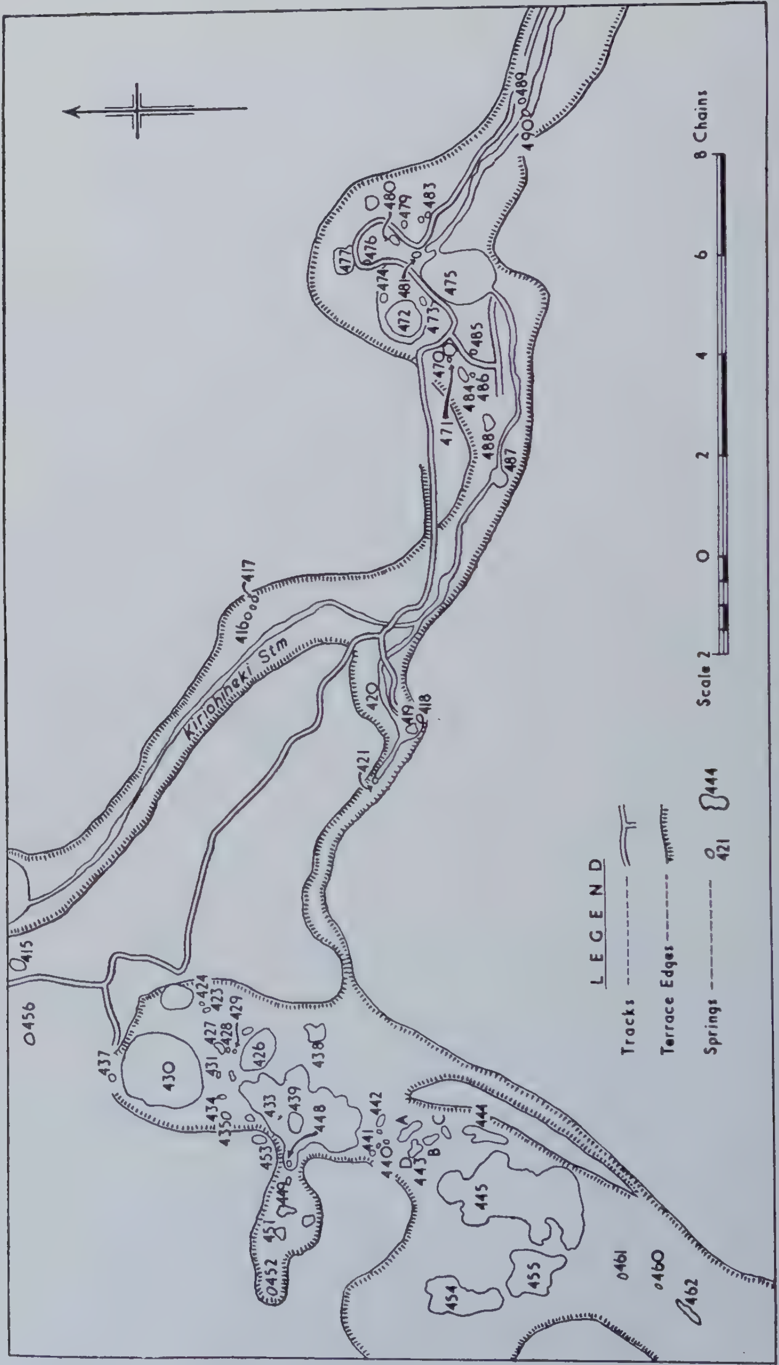

FIG. 1.—Waiora Thermal Area.

pools, and that the water, or other deposits, contribute little or nothing. The notably contrasting thermal areas in this respect are Waiora and Orakei Korako.

The average for the count rates measured in the hot stagnant pools in Waiora is 196 c/m and for the hot springs is 128 c/m. The following hypothesis is advanced to account for the difference in radioactivity. In hot stagnant pools the loss of water is solely by evaporation, so that solid radioactive elements brought into the pool with water will tend to accumulate. In springs, however, some of the radioactive elements will be lost by outflow. If radon enters the pool with the steam or gas, the radioactivity in a stagnant pool will be due to an accumulation of radon's daughter products. If radon ceases to enter, the gamma radioactivity will rapidly drop back to that of the soil.

Soil Radioactivity Measurements

Soil radioactivity measurements did not show any great variation in the areas listed in Table 1, except for the relatively low values at Orakei Korako and Rotokaua, and the one high value obtained at Tarawera. Commonly, a marked difference was observed between steaming ground and cold thermally altered ground—e.g., the steaming ground near pool 76 in the Spa area gave 308 c/m, while the average for soil measurements in the Spa area was 123 c/m.

On the ground near Karapiti fumarole (712) (see Fig. 2), the counting rate was higher than on soils nearby. This was most apparent on the ground below the steam jet, where the soil was moist due to condensation of the steam. Inside the fumarole itself a still greater increase was observed. The author has found the radon content of the emerging gas to be 360×10^{-9} curies/litre (which is of the order of the highest radon concentrations observed in thermal areas in Japan (Kuroda, 1944)), so that radon's daughter products are almost certainly the cause of the high gamma activity observed around Karapiti fumarole.

Variation of Radioctivity with Depth in Pools

For pool 427, curve E (Fig. 3) shows a maximum, while another measurement (curve D, Fig. 3), in a different spot, shows no change. Because of the irregular shape of the walls of the pool and its turbidity, it was not possible to judge the distance between the probe and the wall. However, because of the relatively high constant counting rate up to 10 ft (curve D), it is probable that the probe was lowered in contact with the walls, whereas the one peak (in curve E) suggests that the probe came close to the wall at a depth of 3 ft. The curves of 472 (C), 419 (A), and 418 (B) show that there was more than one radioactivity peak for these pools. Examination of pool 419 showed that these peaks occurred whenever the probe came either in contact with, or close to, a hard ledge. One of these ledges is the surface sinter,

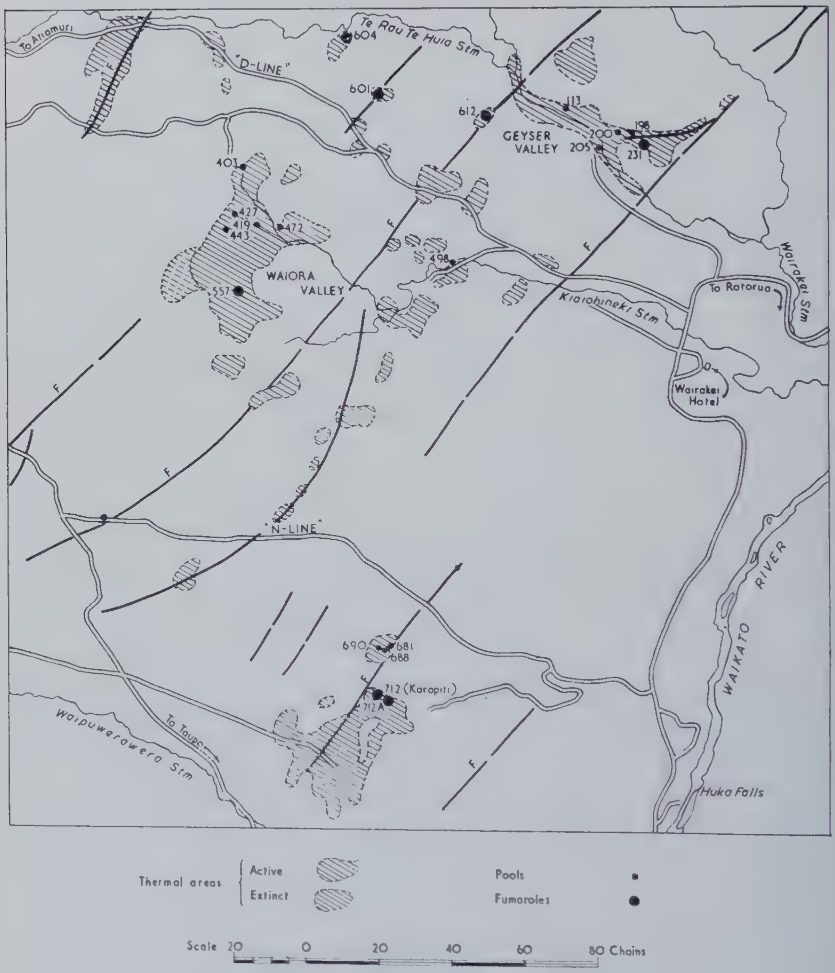

FIG. 2.—Wairakei Thermal Area.

which is comparatively active, but the count rate, as shown in Fig. 3, with the Geiger tube just below the surface of the pool, was low because of its distance from the surface ledge and the attenuating effect of the water. In pool 472, one very active ledge was found at a depth of about 10 ft. As the probe rises above the pool, another maximum is obtained. This can be expected from a consideration of the geometrical and attenuation factors involved.

The water in both pools contains very little radioactivity, but the maxima in the overflow channels of these pools show that radioactive material precipitates out after a little cooling, forming an active surface layer. The high-activity ledges under the surface are probably of similar material to that of the surface ledge. If this is so, they were probably formed when the level of the pool was lower than at present. The lower ledge discovered is deeper than 10 ft in 419, and is 10 ft in 472, which suggests that the precipitate has a comparatively long half-life.

Sinter Activity

The sinters of pools 419 and 472 in the Waiora area are much more radioactive than the Waiora soil. Soil around pool 443a gave a counting rate similar to that of soil in the Waiora Valley, despite the high radioactivity of the pool. The count rate of the probe laid on the sinter along the overflow channel of 419 rose to a maximum of 15 ft from the pool's edge. The sinter along the direction of water flow from pool 472 gave similar results. Radioactivities of sinters in other areas (see Fig. 2 and Table 2) are much lower and comparable with soil activities in these areas. On the other hand, all sinters examined at Orakei Korako (see Table 1) are low in radioactivity compared with the sinteres of other areas. Here the radioactivities of the sinters are even lower than those of the soils.

The author has observed that the Rn concentration in the gas bubbling out of pool 113 (Wairakei) is considerably greater than that observed at pool 419 (Waiora). (There is a much higher rate of gas evolution from pool 113.) The activity in the overflow channel of pool 113 is not greater than that of the soil nearby, while the sinter at

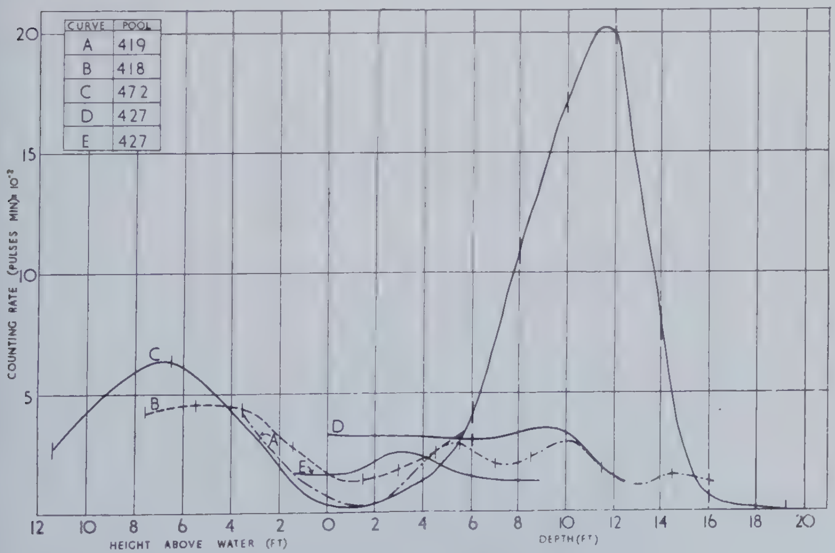

FIG. 3.—Count rate of an 18 in. gamma tube as a function of depth in five pools.

pool 419 is highly active. The temperatures, colours (cloudy blue), and rates of overflow of the two pools are similar, but their pH values are 6 and 2·3 respectively. Waiora and Wairakei are predominantly sulphate and chloride areas (Studt, 1957) respectively. Thus the radioactive sulphates (probably $RaSO_4$) will precipitate out more readily in Waiora pools. Also, the hot acidic water, as at pool 419, will more readily leach the radioactive elements in its passage through the rocks, and bring them to the surface. In this case the gamma radioactivity of the sinter will supply information only about the beds through which the water has passed. This appears to be in agreement with theories propounded in Japan (Kuroda, 1944).

CONCLUSION

The range of gamma radioactivity found in hot pools very close together, and which probably have a common water supply, indicates that the physical and chemical characteristics of a given pool could have a large effect on the gamma activity observed. This is especially true when solid radioactive elements are brought into the pool, as these may be concentrated in the water of stagnant pools or precipitated in the case of springs in the sulphate areas.

It thus appears that a study of radon, an inert gas, and consequently affected only slightly by the characteristics of a given pool, is more likely to yield valuable information about the thermal areas than are gamma radioactivity measurements.

ACKNOWLEDGEMENTS

The author wishes to acknowledge the valuable assistance given by Mr F. B. Knox in both field measurements and their interpretation. Figures 1 and 2 were prepared by Messrs D. Gregg and A. C. M. Laing, of the Geological Survey.

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THE OCCURRENCE OF *ATOMODESMA* BEYRICH IN NEW ZEALAND

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Summary

The lamellibranch genus *Maitaia* Marwick 1934, widespread in the upper Paleozoic deposits of New Zealand, is a synonym of the Timor genus *Atomodesma* Beyrich, 1864. A new species (*A. marwicki*) is described, and the description of *Atomodesma trechmanni* (Marwick) emended.

INTRODUCTION

As Fleming pointed out in 1949, the lamellibranch "*Maitaia*" is the most characteristic fossil of the upper Paleozoic deposits in New Zealand. The genus is easily recognized by the thick prismatic shell with long hexagonal prisms at right-angles to the surface, much as in the Mesozoic genus, *Inoceramus*. The shells are Myalinid in character, biconvex, usually with sharp beaks placed at the anterior margin, and with an ornament of low, gently undulating, concentric wrinkles. Along the hinge is a ligament area striated longitudinally with several strong grooves, and under the beak an umbonal septum is developed in the plane of the commissure. The shells are large, Trechmann (1917) recording one specimen that measured 170 mm in length, and generally inflation is low.

THE HISTORY OF THE DISCOVERY OF *"Maitaia"*

Specimens of "*Maitaia*" were first discovered near Nelson in argillites of the Maitai Group, and were confused for many years with *Inoceramus* by Hector (1870), Hutton (1877), and other geologists, because of the prismatic structure of the shell. To explain the occurrence of *Inoceramus*-like fragments in Palaeozoic strata, one author even suggested that the shells were inorganic. Bell, Clarke, and Marshall (1911), and Marshall (1912, p. 180), on the other hand, used these specimens as evidence for a Mesozoic age for the Maitai Group. Only McKay (1878) suggested that the genus might differ from *Inoceramus*, and prove to be new.

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*At present at the Sedgwick Museum, Cambridge.

N.Z. J. Geol. Geophys. 1: 166–77

In 1917, Trechmann reaffirmed the upper Paleozoic age of the Maitai Group, chiefly from the study of the brachiopods and corals, and compared the mystery species to *Aphanaia mitchelli* (McCoy), a prismatic shell from the Upper Marine Series of New South Wales, Australia. Like the shells from Nelson, this species was originally described as an *Inoceramus*, but was placed in a new genus *Aphanaia* by de Koninck (1877).

The Nelson species did not long remain in this genus, however. In an oral communication to Benson in 1921, Dun stated that *Aphanaia* does not possess the same large posterior ear and ligamental structures as the specimens figured by Trechmann. Marwick (1934) proposed the new genus *Maitaia* for the New Zealand shells, and the type species, *M. trechmanni* Marwick, was described and figured in 1935.

DISTRIBUTION OF "*Maitaia*"

Wellman (1956, p. 25) stated that "*Maitaia*" is by far the most important guide fossil in the upper Paleozoic of New Zealand. Fifty years after its discovery at Nelson, Ongley (1939) found specimens in the Southland Syncline at Clinton (figured in Marwick, 1926), and others were collected and figured by Wood (1956, fig. 23 A, D) from the Arthurton Group near Arthurton. On the southern limb of the Southland Syncline, "*Maitaia*" prisms were noted in the matrix of fossils from the Productus Creek Group (footnote p. 7 in Fletcher, 1952) correlated with the Arthurton and Maitai groups, and better specimens were collected by Mr A. R. Mutch and the writer in 1955. An internal cast was figured by Wood (1956, fig. 18) from the Waipahi Group underlying the Arthurton Group, and to the south, fragments have been found in the correlative Takitimu Group underlying the Productus Creek Group (Mutch, 1957, p. 501). Internal casts have also been found in the Te Anau Group below the Maitai Group near Nelson. As pointed out by Trechmann (1917, p. 56, pl. 4, fig. 8), prismatic fragments of "*Maitaia*" are easily recognized, and even after leaching leave characteristic holes in the rock, with the prismatic structure still visible on the cast. Such casts and fragments have been reported by Wellman and Willett (1947) from Colac Bay and the Livingstone Range, and these writers, with Mutch (1957), give a summary of other discoveries in Southland, Otago, Marlborough, and Nelson.

Prismatic shell fragments are also known in the upper Permian Waipapa Series in North Auckland (Dr C. A. Fleming, pers. comm.), despite a statement to the contrary by the writer (Waterhouse, 1956, p. 587).

In New Caledonia, specimens of undoubtedly the same genus were recorded as *Maitaia trechmanni* by Avias (1953) from beds correlated with the Maitai Group, and fragments were also discovered from the underlying "Formation of Polycoloured Tuffs," correlated with the Te Anau Group.

Licharew (1934, p. 125, pl. 10, figs. 7–10, 13, 17) compared fragments of a thick prismatic shell from the ?Permian of the Kolyma Peninsular, Russia, with the specimens described by Trechmann (1917), and referred the shells to *Aphanaia*. These specimens have been examined by Newell (1942), who states that ligamental grooves are not developed.

COMPARISON WITH *Aphanaia*

There are two Australian Permian genera with a thick prismatic shell. One of them, *Pseudomyalina* Dickins, is easily distinguished, for the left valve is larger than the right, fine radial costae are present, the umbonal septum is not developed, and the muscle scars differ considerably (Dickins, 1956, text-fig. p. 27). On the other hand, *Aphanaia* Koninck has long invited comparison with the New Zealand shells, and as recently as 1949 Reed referred to "*Maitaia* (*Aphanaia*) *trechmanni*." Unfortunately, the holotype of *Aphanaia gigantea* Koninck has been destroyed by fire, but other specimens have been examined at the Australian Museum, Sydney, and at Sydney University. Some of these shells are huge, the maximum dimension of one specimen exceeding 12 inches. The nature of the hinge could not be determined, but the posterior muscle scar and part of the pallial line are well displayed on decorticated specimens, particularly Specimen F 10951 (see Fig. 1B) at the Australian Museum. Specimen 2180 at Sydney University shows part of the muscle scar and pallial line. The posterior muscle scar is somewhat like that of the New Zealand species, although placed closer to the ventral surface, but, whereas the concave edge of the scar in "*Maitaia*" usually faces the beak, it faces the hinge in *A. gigantea*; also, the posterior or dorsal lobe of the scar is smaller than the anterior or ventral lobe in New Zealand species, but in the Australian shell it is the ventral lobe which is smaller. These differences are illustrated in Fig. 1. As in the New Zealand shells, the groove-like pallial line has

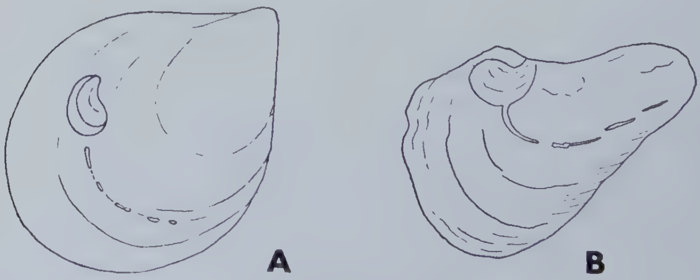

FIG. 1.

A: Internal cast of right valve of *Atomodesma* from GS 4586 (Specimen TM 2037)), Arthurton Group. Half natural size, approximately.
B: Internal cast of right valve of *Aphanaia gigantea* Koninck sketched from Specimen F 10951, Australian Museum, Sydney. One-fifth natural size, approx.

short muscle pits along its length, and the shell shows low radial striae, and even radiating bands of light and dark shell, recorded by Wood (1956, fig. 23 D) in the specimens from Arthurton. But until the hinge is known, no certain relationship can be determined.

Inoceramus mitchelli McCoy was designated as type species of *Aphanaia* by Newell (1942). The type specimen, a poorly preserved internal cast, has been examined at the Sedgwick Museum, Cambridge. A single ligamental groove is developed along the hinge, and on this basis the species was relegated to *Atomodesma* Beyrich by Dickins (1956, p. 22), who was first to describe the hinge accurately. It is doubtful, however, if *I. mitchelli* can be definitely assigned to *Atomodesma*. The Australian species is inequivalve, and the umbonal septum characteristic of *Atomodesma* (see below) is lacking as far as can be seen, although there is no certainty because the beaks of McCoy's specimen are slightly damaged. The posterior muscle scar is vaguely defined, more or less oval in shape, with a slightly concave edge facing the beak.

IDENTIFICATION OF *Maitaia* WITH *Atomodesma*

The collections of the types and other specimens of most species of *Atomodesma* Beyrich from Timor have been examined at museums and institutes at Bonn, Amsterdam, Utrecht, and Delft. It has been found that *Atomodesma* is not only similar in external appearance and prismatic shell, as noted by Newell in 1942, but is identical in the nature of the hinge and the presence of the umbonal septum. The specimen that shows this identity most convincingly is figured by Wanner (1940, p. 376, text-fig. 1) as *A. variabilis* Wanner, examined at Amsterdam. An umbonal septum is developed and two ligamental grooves lie next to the hinge. The trace of a third is visible near the umbo. Another specimen of this species (Wanner, 1922, pl. 153, fig. 4) also has two ligamental grooves, with some evidence of an umbonal septum, and a tiny unfigured specimen in the collection at Bonn has a well developed septum, although the shell is only 14 mm long. Three ligamental grooves are present in *A. exarata* figured in Wanner (1922, pl. 153, figs 9a, b), and at Utrecht an unfigured specimen (818 L), identified with this species by Rothpletz (1892), has one or two grooves and an umbonal plate. Otherwise, one groove is present along the hinge. Dickins (1956) supposed that only one ligamental groove is present as a characteristic feature of *Atomodesma*, in contrast to "*Maitaia*" with several grooves, but the Timor species have from one to three grooves despite their small size. To this author goes the credit of pointing out that an umbonal septum is present in both genera. In many Timor species, the ligament area lies approximately at right-angles to the commissure of the valves, whereas in the Nelson shells the ligamental area twists anteriorly into a "horizontal" position, lying in the plane of the commissure near the beaks. In some species such as *A. variabilis* Wanner and a new species from New Zealand, described below, the hinge extends a little in front of the beak, and a small anterior ear is formed.

Generally the species from Timor are less than half the size of the shells from Nelson and Arthurton, but a large specimen figured as *Mysidopteria* sp. by Wanner (1922, pl. 154, fig. 1) and measuring 90 mm diagonally might be *Atomodesma*—the radial costae of the figure are greatly exaggerated. Radial plicae occur in a number of Timor species, but are not considered to be of generic importance, because the number varies widely, and plicae are not present in a number of species.

SYSTEMATICS

Atomodesma Beyrich, 1864; emend. Wanner, 1922 and 1940; emend.

?1847 *Inoceramus* McCoy, Ann. Mag. nat. Hist., 20: 299.
1864 *Atomodesma* Beyrich, Abh. Akad. Wiss. Berlin: 61–98.
1870 *Inoceramus* Hector, Cat. Colon. Mus., p. 196.
?1877 *Aphanaia* Koninck, Mem. Soc. Sci. Liége, 2 (2): 302.
1892 *Atomodesma* Rothpletz, Palaeontographica, 39: 85.
1917 *Aphanaia* Trechmann, Geol. Mag., dec. 6, 4: 56.
1922 *Atomodesma* Wanner, Pal. Timor, 11 (18): 63.
1934 *Maitaia* Marwick, Proc. 5th Pacif. Sci. Congr.: 948.
1935 *Maitaia* Marwick, Trans. roy. Soc. N.Z., 65: 295.
1940 *Atomodesma* Wanner, Geol. Exped. to Lesser Sunda Islands, 2: 376.
?1942 *Aphanaia* Newell, Bull. Kans. geol. Surv., 10 (2): 76.
1956 *Maitaia* Wood, N.Z. geol. Surv. Bull. 53: 49.

DIAGNOSIS. Small to very large usually biconvex shells, beaks anterior, proso- or orthogyrous, a small anterior ear in some species, a large posterior ear common, shell elongated diagonally. Ornament of low concentric wrinkles or one to several radial plicae. Ligament area largely or entirely posterior, edentulous, with one to six well defined longitudinal grooves. Septum in both valves. Shell thick and prismatic, with a thin lamellar layer. In New Zealand species: posterior adductor scar large, posteriorly placed, rounded ventrally, concave towards the beak, the lobe near the hinge small. Pallial line with elongated discontinuous muscle scars. The shell may show radial black and light bands.

Permian of Timor, Salt Range and Karakorum Range, Western and ?Eastern Australia, New Caledonia, and New Zealand, possibly southwest Africa (Reed, 1935).

TYPE SPECIES. *Atomodesma exarata* Beyrich, 1864. (By subsequent designation, Wanner, 1922, p. 63.)

DISCUSSION. *Inoceramus mitchelli* McCoy, the type species of *Aphanaia*, is doubtfully congeneric, as no umbonal septum is known in this species, and the shell is equivalve. A species identified from the Salt

Range by Waagen (1887, p. 274) is doubtfully congeneric, but a species from the Salt Range has been described by Reed (1944). *Aphanaia salinaria* Reed 1944 shows no resemblance to *Aphanaia* or *Atomodesma*, and looks closer to *Promytilus* Newell. The species figured as *Aphanaia haibensis* Reed (1935), from the Upper Dwyka beds of South-west Africa, may belong to *Atomodesma*, and a species described by Merla (1934) from the Karakorum Range is also probably congeneric.

Atomodesma trechmanni (Marwick), 1934, emend. Fig. 2 B

1870 *Inoceramus* Hector, Cat. Colon. Mus.: 196.
1871 *Inoceramus* Davis, N.Z. geol. Surv. Rep. geol. Explor., 1870–71: 107.
1877 *Inoceramus* Hutton, N.Z. geol. Surv. Rep. geol. Explor., 1873–74: 34.
1878 ?New Genus McKay, N.Z. geol. Surv. Rep. geol. Explor., 1877–78: 132.
1904 *Inoceramus* Park, Trans. N.Z. Inst., 36: 438, 440.
1910 Inorganic; Park, Geology of New Zealand, p. 51.
1911 *Inoceramus* Bell, Clarke and Marshall, N.Z. geol. Surv. Bull. n.s. 12: 19.
1917 *Aphanaia* sp. cf. *mitchelli* McCoy; Trechmann, Geol. Mag., dec. 6, 5: 56, pl. 4, figs 1–4, 8.
1919 *Aphanaia* Morgan, N.Z.J.Sci. Tech., 2: 34.
1921 not *Aphanaia* Benson, Aust. Ass. Adv. Sci., 15: 18.
1934 *Maitaia trechmanni* Marwick, Proc. 5th Pacif. Sci. Congr.: 948.
1935 *Maitaia trechmanni* Marwick, Trans. roy Soc. N.Z., 65: 295, pl. 34, figs 1–3.
1942 *Maitaia trechmanni*; Newell, Univ. Kansas Publ., 10 (2): 76, fig. 22 B.
1949 *Maitaia* (*Aphanaia*) *trechmanni*; Reed, The Geology of the British Empire, p. 638.

MATERIAL. The holotype (N.Z. Geological Survey Collection, TM 2033) is an internal cast of an immature left valve, with the beak, posterior part of the hinge, and the muscle scars and pallial line destroyed, but showing clearly the umbonal septum and anterior part of the hinge. Marwick's paratype (TM 2034) is a poorly preserved posterior-ventral part of a decorticated specimen showing the posterior muscle scar. Most of the specimens described by Trechmann are very large flattened internal and external casts, showing the hinge clearly. Trechmann also figured a small valve.

LOCALITY. Argillites at Wooded Peak, Maitai Group, GS 143, Nelson.

DESCRIPTION. Large equivalve little-inflated shells, mytiliform, with terminal weakly prosogyrous beaks. The umbonal angle measures 70°. Maximum inflation lies close to the anterior margin, at 70° from the hinge. Posterior wing large, most prominent in small specimens. Sculpture of low concentric wrinkles, varying in intensity on different individuals, some specimens being almost smooth, together with traces of fine radial striae, about 3 occurring in 2 mm. The hinge extends a little in front of the beak, but is almost entirely posterior, strongly thickened, edentulous, with 3 to 6 grooves on the ligamental area in mature specimens. The anterior half of the area lies in the plane of the commissure of the valves, and from mid-length it usually twists gradually outwards through 30° to 40°. Under the beak the area is concave and constricted, the inner margin convexly approaching the beak, and interrupting the lower two to three grooves, so that only the upper ones extend under the beak to the anterior margin. The grooves are parallel to each other, but are slightly oblique to the hinge, from which they diverge posteriorly, the outer grooves stopping at the outer margin, and new grooves arising from the inner margin. Umbonal septum well developed, with an angle of 40° to 50° except in some of Trechmann's specimens, which are crushed and prolonged posteriorly for half of the length of the hinge as a narrow ledge. Pedal, retractor, and posterior adductor scars together form a large well defined impression placed moderately close to the dorsal posterior margin; somewhat bean-shaped, rounded posteriorly and concave anteriorly, the dorsal lobe smaller than the ventral. Pallial line probably parallel to growth-lines for its visible length, probably with several elongated visceral retractor scars. Anterior part and anterior muscle scars unknown. Shell consists chiefly of the prismatic layer.

REMARKS. Examination of the specimens figured by Trechmann (1917) and kept at the British Museum of Natural History in London has provided information on the beaks, hinge, and muscle scars in addition to that available to Marwick. At the anterior end of the posterior muscle scar, Marwick (1935, pl. 34, fig. 1) sketched an elongated depression directed ventrally across the growth lines, this supposedly representing the pallial line. Examination of the specimen shows that this depression is simply a strip of shell exposed between shell covered with matrix on each side, and that there is no real depression in such a position. In the specimens from Arthurton, the pallial line follows the growth lines, and the Nelson shells are assumed to be similar. The bean-shaped posterior muscle scar is visible on Marwick's paratype, TM 2304 (the anterior-dorsal margin is incorrectly shown as straight, or incomplete, in the figure, pl. 34, figs 1, 3) and on the specimen partly figured by Trechmann in pl. 4, fig. 1.

Usually only the prismatic shell is preserved, but fragments of shell in black calcareous argillite at GS 6323, Productus Creek Group, have a thin outer layer of fibrous shell, barely a twelfth of the thickness of the prismatic layer. Nearby specimens from GS 6072 are of interest in that they have a well-defined byssal notch at the anterior margin.

Pending closer study, the specimens from Clinton, Arthurton, and Productus Creek will not be referred to *A. trechmanni*, although of the same age. In the fragment identified with this species from New Caledonia by Avias (1953, pl. 7, figs. 4a, b), the umbonal septum has a wide angle close to 90°, like that of the specimens from GS 4586 and GS 4652 of the Arthurton Group. The angle is only half as great in specimens of *A. trechmanni* from the type locality.

AGE. The Maitai Group is correlated with the Upper Marine Series of New South Wales and Ingelara Stage of Queensland. Probably Kungurian.

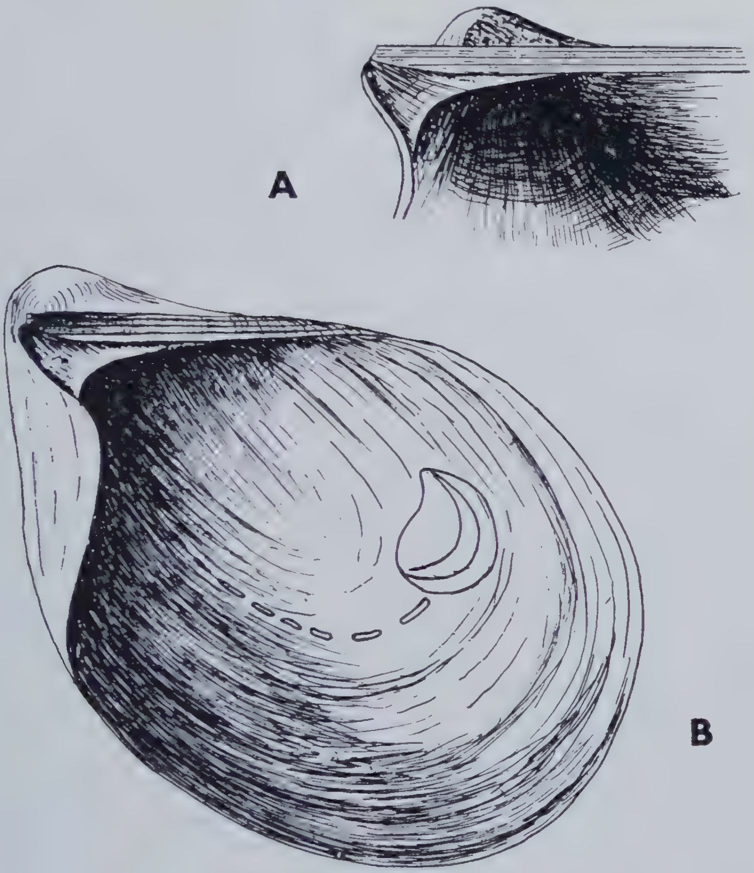

FIG. 2.

A: *Atomodesma marwicki* n.sp., showing beak and anterior ear of the right valve. Compare the position of the septum with that of *A. trechmanni*, figured below. Sketched from rubber mould of the holotype, TM 2035. Approx. × 2·4.

B: *Atomodesma trechmanni* (Marwick), a generalized sketch reconstructed from several specimens. Muscle scar and pallial line copied from Arthurton specimens. Approximately four-fifths natural size.

Atomodesma marwicki n.sp. Fig. 2A.

1956 *Maitaia* sp. Marwick, in Wood, N.Z. geol. Surv. Bull., 53: 38, fig. 18.

MATERIAL. The holotype (N.Z. Geological Survey Collection, TM 2035) is an internal cast of the two valves resting in an open position. The umbonal region, with the umbones, hinge, and umbonal septum, is well preserved, but the posterior part of the shell is cracked and displaced, and the posterior, ventral, and part of the anterior margins destroyed. An internal cast of the posterior part of two conjoined valves (TM 2036) is available from Nelson. In this specimen the hinge is not as well preserved. Neither specimen shows the muscle scars or pallial line.

Localities. Hill-top at Trig. X, The Cone, GS 5082, Waipahi Group, Southland. Boulders derived from the Te Anau Group, at junction of Collins and Whangamoa rivers, GS 3757, Nelson.

Diagnosis. This species is distinguished by the well developed anterior ears, with the septum placed below the ears, instead of under the beaks.

Description. As the valves are broken, the shape and dimensions are imperfectly known. The length exceeds 47 mm, the height exceeds 40 mm, and the width of the valve near the beak is 12 mm. The umbones are weakly prosogyrous, with a narrow umbonal angle of 60° a little below the tips. In front is a small anterior ear of equal size in both valves, and less than a sixth of the entire length of the hinge. The cardinal angle is acute, the dorsal margin meeting the anterior margin at 60° to 70°, and the anterior margin of the ear is gently rounded. Near the anterior margin the shell is well inflated, the maximum inflation lying at 45° from the hinge. Posteriorly inflation is low, and large posterior ears are developed. Sculpture comprises low growth-lines, but the shell is almost smooth.

The ligamental area is inclined dorsally from the commissure of the valves at about 35° throughout its entire length, and is weakly concave with 3 or 4 ligamental grooves, and longitudinal striae. It extends to the anterior margin, and is only slightly constricted anteriorly above the septum. Thickening along the hinge seems to be small. The septum does not lie under the beak, but beneath the anterior ears. Near the hinge, the angle enclosing the septum is 70°, this angle diminishing to 50° posteriorly. The septum is prolonged posteriorly for less than a quarter of the length of the hinge. Muscle scars and the pallial line are unknown.

The internal cast (TM 2036) from Nelson is identical in shape, with similar narrow slightly more prosogyrous umbones, a moderately well-developed anterior ear, with the septum placed as in the holotype. Unlike the holotype, it has well developed concentric wrinkles; the same variation occurs in *A. trechmanni*, in which most specimens are smooth, but some concentrically wrinkled. From the largest and most complete of these growth-wrinkles, the width of the shell at one stage measured 29·5 mm, the length 34·0 mm, and the height of each valve 11·0 mm. The hinge at this size is about 19 mm, and the ears more than a tenth of the length of the hinge. The complete specimen must have been at least twice as large.

Remarks. A good photograph of the holotype is given in Wood (1956, fig. 23) at twice natural size, approximately.

This species is very distinctive because the anterior ear is lacking from the younger species of *Atomodesma* in New Zealand, and because of the unusual position of the septum. In species from Timor, an anterior ear is well developed, in *A. variabilis*, for example, but unfortunately the position of the septum in relation to the ear was not noted. The Waipahi specimen does not appear to be conspecific with specimens of *Atomodesma* from the Takitimu Group, although the two are considered to be of approximately the same age. Unless crushing has distorted the specimens, a small anterior ear is developed in the Takitimu shells, but the umbonal septa are different, lying largely beneath the umbones, not beneath the ears.

AGE. The age is uncertain, but, from work now in progress, may be Artinskian.

CONCLUSIONS

Maitaia Marwick 1934 is identical with *Atomodesma* Beyrich 1864, as both genera have a prismatic shell, similar appearance, with one to six ligamental grooves along the ligamental area, and an umbonal septum. New Zealand species are generally larger, and lack the radial plicae that are characteristic of a number of Timor species. The identification of *Aphanaia* Koninck suggested by Dickins (1956) cannot yet be proven, as the type specimen of *Aphanaia* seems to lack an umbonal septum. The posterior muscle scar of *A. gigantea* Koninck is somewhat similar to that of *A. trechmanni* (Marwick), but, whereas the concave side faces the beak in the New Zealand species, it faces the hinge in the Australian form, and in the Australian form the narrow end of the scar is not dorsal, but anterior. The pallial line is similar in both forms.

A new species of *Atomodesma* occurs in the Waipahi Group of Southland and Te Anau Group of Nelson, and is distinguished from *A. trechmanni* by the presence of a small anterior ear. The septum does not lie under the beak, but under the ear.

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THE WELLINGTON FAULT FROM COOK STRAIT TO MANAWATU GORGE

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Summary

Air photo interpretation of Recent and Late Pleistocene faults shows the Wellington Fault to be a transcurrent clockwise (dextral right-lateral) fault extending from Cook Strait to the point west of Lake Waikaremoana, where it branches into several branch faults extending into the Bay of Plenty. Details are given of Recent displacements along the Wellington Fault between Cook Strait and the Manawatu Gorge.

INTRODUCTION

A map of New Zealand showing the "Principal Faults and Earthquake Rents" by McKay (1892) accompanied the first report in which the Wellington Fault is mentioned. McKay realised that faulting is generally an expression of tectonic forces affecting large areas and showed a system of straight faults linking both islands. It is irrelevant whether McKay arranged the faults exactly as they are now known; the fact that he placed the faults in a system is all important.

The Wellington Fault (Fault No. 4 of McKay) is described by him (1892, p. 19) as "the line that forms the abrupt western shore of Wellington Harbour between Kaiwarra [Kaiwharawhara] and Petone, and, beyond Petone follows the general direction of the Hutt Valley. Beyond that it has not been traced."

Bell (1908) described the abrupt north-west coast of the Wellington Harbour and assumed it to be controlled by one of the fault planes "forming a graben extending from Cook Strait north-eastwards up the Valley of the Hutt River." In 1910 (p. 538) he described "The Great Fault along the western side of the Wellington Harbour" as having a throw not less than 500 feet.

Cotton (1912a) identified the western shore of the Wellington Harbour as a clearly defined fault scarp of recent origin. The reasons given being the absence of rock platforms, fault-formed terminal facets, and the depth of 12 fathoms a short distance offshore. In a further paper Cotton (1912b) named this the Wellington Fault and again accepted the cliffed western shore as the fault scarp, which was mapped southwards to the Tinakori Valley. Later, Cotton (1914) accepted the Upper Kaiwharawhara and Silver Stream valleys as fault-line valleys and extended the Wellington Fault southwards to Cook Strait. Northwards, he accepted the continuous scarp along the west side of the Hutt Valley as at least in part a fault scarp and tentatively suggested "that the valley of the Hutt River to its very source is determined by a line of faulting which continues the line of the Wellington Fault." Cotton (1916) described the west coast of the Wellington Harbour as a one-cycle fault coast stressing the youthfulness of the scarp and in 1921 (a and b), 1922, 1923, 1937, and 1942, again described the Wellington Fault.

Mackenzie (1929) and Quennell (1938) described fault and fault-line features in the Hutt Valley area and accepted Cotton's interpretation.

Hall (1946) estimated the latest movements along the Wellington Fault to be late Pliocene as indicated by "the width of the wavecut platform fronting the scarp and the cliffing at the inner margin of the platform, cliffs of about 100 ft high backing a 4-chain platform." The wide belt of crushing was used as evidence for thrusting, rather than for normal faulting.

Adkin (1949, see map) showed the Wellington Fault as a normal fault extending from Tinakori Valley north-east beyond Upper Hutt.

Cotton (1950) discovered two shutter ridges at the extreme southern end of the fault and presented the first record of recent transcurrent movement along this fault. In 1951 he abandoned the theory of two-cycle origin of the fault-line scarp and considered the Wellington Fault to have a large clockwise transcurrent component. Later Cotton (1953) regarded the Recent movements along the Wellington Fault as transcurrent, but implied that pre-Recent movements had been predominantly normal.

Adkin (1954) described the Wellington Fault as a predominantly normal fault.

Stevens (1956, 1957) described the western side of the Hutt Valley as a fault-line feature and showed on his map (1956, fig. 2) clockwise transcurrent displacements along the Wellington Fault near Maori Bank in the Hutt Valley.

Wellman (1953) suggested linking the Wairau, Clarence, Hope, Awatere and other faults with the Alpine Fault, thereby accepting McKay's concept of a regional fault pattern. He showed that these faults are essentially clockwise transcurrent. This clockwise direction of transcurrent movement has since been independently confirmed by Eiby (1955) from seismological data.

TABLE OF DATA

In listing the available air photo interpretation data (Table 1) the writer has for general uniformity adopted the system used by Wellman

TABLE 1.—Data from interpretation of air photographs, arranged according to the system adopted by Wellman (1953, p. 279).

								Dip	Displacement				
									Vertical		Horizontal		
Ref. No.	N.Z.M.S. 1	Grid Ref.	Airphoto No. (Lands and Survey Index)	Locality	Nature	Length (ft)	Strike	Direction	Upthrow side	Amt. (ft)	Direction	Amt. (ft)	Ref. surface or line
1.	2.	3.	4.	5.	5.	7.	8.	9.	10.	11.	12.	13.	14.
1	N164	268154	174/5	SW of Silver Stream	Sh	cont.	035°				C	230/300	spurs (2)
2	N164	276165	174/6	Along east bank of Silver Stream	Os	cont.	035°	NW	NW	15	C	300	stream
3	N164	283172	175/9	Silver Stream	Os	cont.	035°		NW	10	C	230	stream
4	N164	288182	175/10	Silver Stream	Os	cont.	035°				C	300	stream
5	N164	292185	175/10	Silver Stream	Os	cont.	035°				C	260	stream
6	N164	294188	175/10	NE of Silver Stream	Sh	cont.	035°				C	300	spurs (2)
7	N164	297193	176/12	Karori Stream	Sh	cont.	035°				C	260	spurs (2)
8	N164	328232	177/16	West of Tinakori Road	Sh	3,000	035°				C	250	spurs (4)
9	N164	330236	177/17	SE. slope of Tinakori Hill	Sh	5,000	035°				C	260	spur
10	N161	618441	20B/6	South of Brown Owl	R	cont.	063°		NW	5	C	25	flat edge of flood plain
11	N161	634450	322/28	Emerald Hill	R	cont.	058°		NW		C	230	terrace
12	N161	677473	321/32	SE. of Benge Creek	R	cont.	061°	SE	NW	5	C	40	flat
13	N161	685476	321/32	S. of Benge Creek	Sh	cont.	062°	SE	NW	10	C	270	spur
14	N161	752476	321/39	S. of the Puffer Track	Sh	cont.	062°	SE	NW	5	C	110	spur
15	N161	756477	321/40	SE. of the Puffer Track	R	cont.	062°		NW		C	75	slope
16	N161	697480	321/33	Near Benge Creek	R	cont.	075°	SE	NW	5	C	100	terrace
17	N161	762482	321/39	Puffer Saddle	R	cont.	062°		NW	5			saddle, fault gap
18	N161	750482	321/38	NE. of the Puffer Track	R	2,000	064°	SE	NW	5	C	20	steep slope
19	N161	765484	321/41	NE. of the Puffer Track	Sh	cont.	062°		NW	10	C	120	spur
20	N161	768485	321/41	NE. of the Puffer Track	Sh	cont.	062°		NW	10	C	130	spur
21	N161	774486	321/42	W. of Smith Creek	R	cont.	062°		NW		C		steep slope
22	N161	776510	320/20	Dobson Hut	R	600	045°		NW	10	C	100	ridge
23	N157	994895	895/3	E. of Pukekino	P	4,000	030°		NW		C	180	spurs
24	N161	286159	—	Cone Saddle	R		040°		NW	15	C	100	fault gap

25	N161	287163	—	Look Out	R		030°		NW	—	C		fault gap
26	N157	299185		Cow Saddle	R		035°		NW	10	C	70	saddle, fault gap
27	N157	296176	—	Saddle below Baldy	R		030°				C		trace
28	N157	294172	—	W. of Mangatarereatiwhakatu R.	R		030°				C	150	spur
29	N157	295170	—	E. of Pigs Flat	R		030°				C		spur
30	N157	294170	—	W. of Mountain House	R		035°				C	150	saddle, fault gap
31	N156	284646	315/26	E. of Kime Hutt, NE Mt Hector	R		032°				C	25	2 spurs
32	N153	304196		S. of Ngamaia Stm	R		032		NW	5	C	250	shutter ridge
33	N153	303195		Saddle below Kohu	R		035°		NW	—	C	—	trench
34	N153	302193		Saddle below Herepai	R		035°		NW	—	C	—	rent
35	N153	305197	892/3	W. of Mangatainoka River	R	cont.	030°	NW	NW	10	C	250	terraces, ridge
36	N153	304197	892/3	W. of Mangatainoka River	R	cont.	030°	NW	NW		C	200	spurs, terrace
37	N153	071041	890/4	W. of Mangaroa Road	R	cont.	030°		NW	10	C	180	spur, stream
38	N153	071041	890/4	W. of Mangaroa Road	R	cont.	030°		NW	10	C	120	spur, stream
39	N153	073042	890/4	W. of Mangaroa Road	R	cont.	030°	NW	NW	10	C	160	terrace, spur
40	N153	312100	887/3	N. of Mangahao River	R	cont.	030°		NW	5	C	150	terrace
41	N153	312310	887/3	Across Mangahao River terrace	R	cont.	035		NW	5	C		terrace
42	N153	315216	885/3	W. of Kopokiko Road	Sh	cont.	030°		NW	10	C	150	spur
43	N153	317218	884/3	N. of Naenae Road	R	cont.	030°				C	200	spurs, stream
44	N153	318219	883/4	Headwaters Tamui Stream	Sh	cont.	028	NW	NW	5-10	C	130	spurs
45	N153	317218	884/3	N. of Tamui Valley Road	R	cont.	027°		NW	5-10	C	150	terrace
46	N149	177201	243/7	W. of Mangahao River	Os	cont.	030°		NW	10	C	150	spurs, stream
47	N149	185212	243/7	W. of Mangahao River	R	cont.	030°		NW		C	160	slope, stream
48	N149	191232	243/8	W. of Mangahao River	R	cont.	038°	NW	NW	10-15	C		terrace, foothill
49	N149	207251	243/8	W. of Matarua Creek	R	cont.	030°	NW	NW	10	C	120	streams
50	N149	212258	241/10	W. of Matarua Creek	R	cont.	030°	NW	NW		C	220	spur, stream
51	N149	228278	241/10	W. of Valley Road	Os	cont.	038		NW		C	200	spurs, streams
52	N149	231285	241/11	W. of Valley Road	R	cont.	036°		NW		C	100	spurs
53	N149	233287	240/10	Valley Road	R	cont.	036°	NW	NW		C	200	spur
54	N149	246306	240/11	W. of Ballance	R	cont.	037°	NW	NW		C	200	spur
55	N149	260323	239/12	NW. of Ballance	R	cont.	040°	NW	NW		C	200	stream
56	N149	263326	239/13	NW. of Kahuki	R	cont.	040°		NW	10	C	260	stream

(1953, p. 279). Some additions have, however, been made which are listed below:

Column 6: Nature of fault trace features.
(Sh) stands for shutter ridge.
(P) stands for fault pond.
(OS) stands for offset stream.
Column 7: Length in feet.

The length given refers to the fault trace and not to the particular feature.

The vertical displacements are measured to the nearest 5 ft. and have been checked by independent methods both in the field and by parallax bar on the air photographs.

GENERAL DESCRIPTION OF SURFACE FEATURES

General

The surface expression of the Wellington Fault (Fig. 1) varies considerably, depending on rock induration. In the well indurated greywacke the fault continues in general as a very distinct and straight rent, irrespective of the direction of the bedding in the greywacke. In the less indurated Tertiary and Recent strata the surface features become less straight, less clear, and less continuous.

The Wellington Fault determines clearly the eastern margin of the Ruahine and the northern Tararua ranges over much of their length. The West Wairarapa Fault (Fig. 2) controls the eastern margin of the Rimutaka Range and the south part of the Tararua Range.

Successive Terrace Displacements during Progressive Downcutting

Wellman (1952, 1955b) described the importance of terrace displacements as a guide to rates of fault movement. In a terrace flight at the Maruia River, he showed that a direct relation exists between the height of the terraces and the amount of their total displacement by the Alpine Fault. He explained this direct relation by assuming both a constant rate of river downcutting and a constant rate of faulting. This presupposed that fault displacements exercise no direct control on the rate of downcutting, the two being mutually independent and related only because of their apparent constancy over a given time period (Table 1. Ref. No. 11).

Shutter Ridges, Offset Streams, Captured Streams, and Fault Ponds (Fig. 3.)

Lateral displacement along a transcurrent fault in well dissected country offsets ridges, spurs, etc. As a result the drainage may be diverted or even reversed by capture.

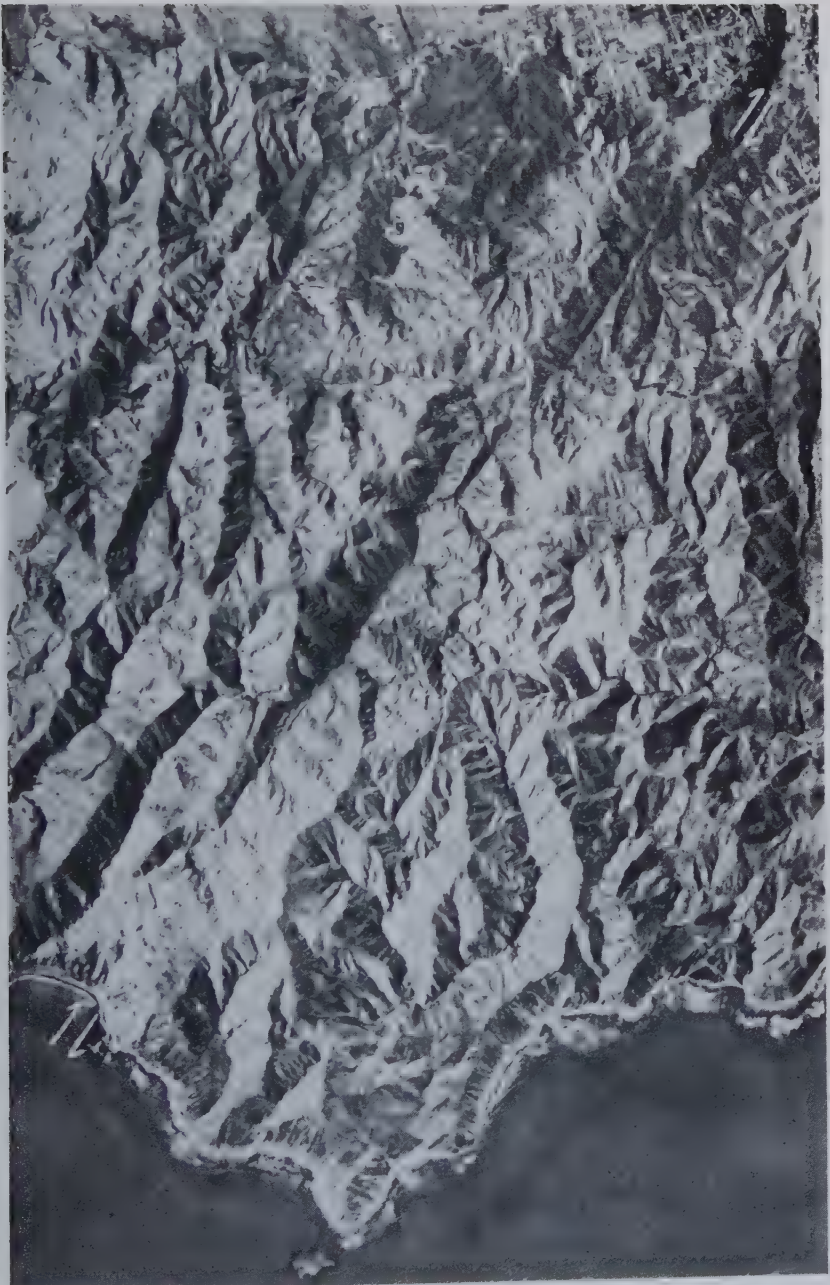

FIG. 1.—Photo-mosaic of the Wellington Fault south of Wellington (published with the permission of the Surveyor General of the Department of Lands and Survey).

SHUTTER RIDGES (TABLE 1. REF. NOS 1, 6-9, 13, 14, 19, 20, 31, and 33)

The shutter ridges (small laterally displaced spurs) along the Wellington Fault are so clear and sharp that it is sometimes difficult to realize that the displacement is the result of numerous successive movements that are recorded by the younger neighbouring terraces.

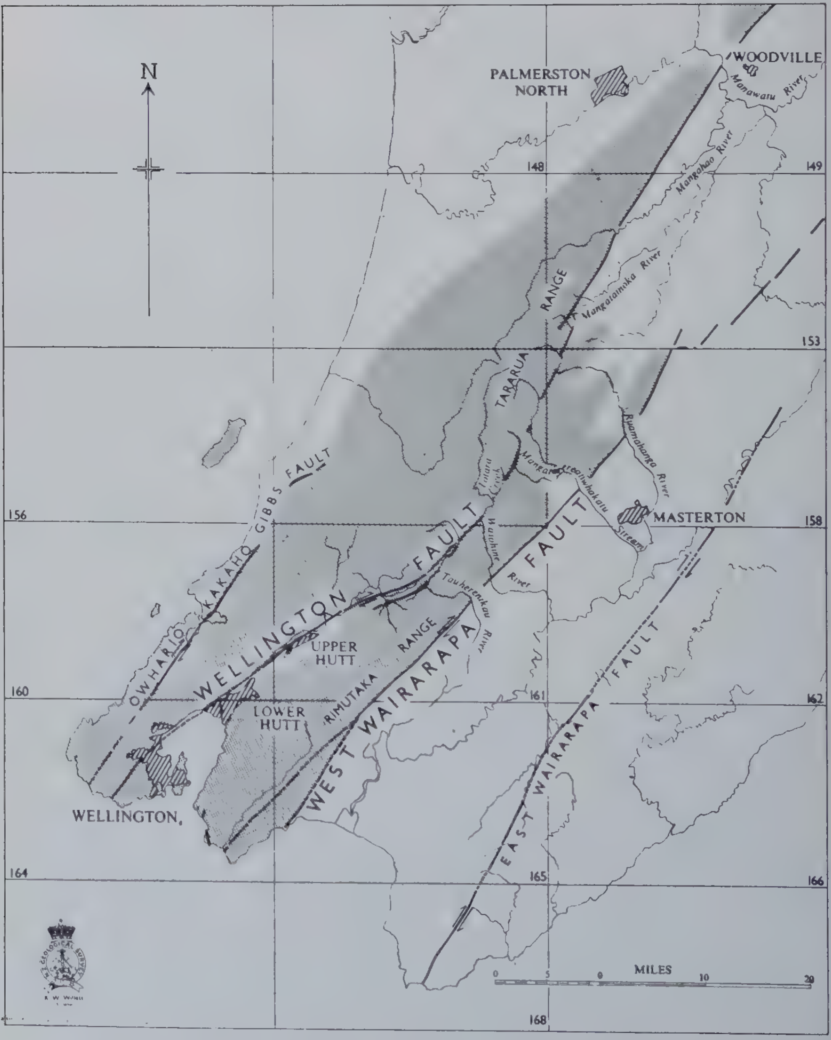

FIG. 2.—Locality map showing the Wellington Fault and the other active faults at the southern end of the North Island. Pre-Cretaceous rocks shaded.

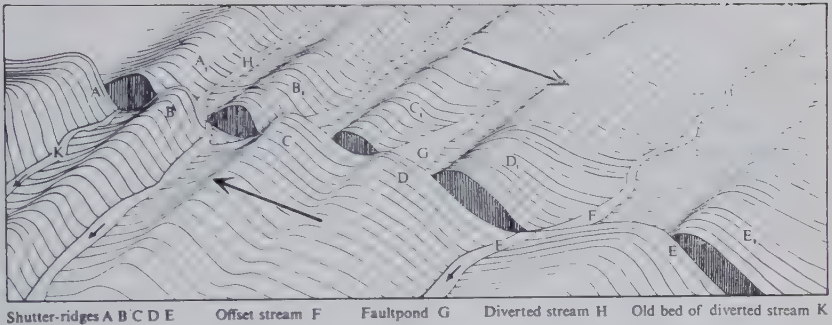

Fig. 3.—Diagrammatic representation of transcurrent fault features: Shutter Ridges AA, BB, CC, DD, EE, Offset Stream F, Faultpond G, diverted Stream H, and old bed of diverted stream K. Sense of movement of fault shown by arrows.

Offset Streams and Diverted Streams

When shutter ridges are formed the interspur streams and gullies are offset. Repeated lateral movement sometimes results in ponding of streams, followed by diversions along spillover courses. It should be noted that offset streams (Table 1. Ref. Nos 2, 3, 4, 5, 25, 26, 32, 35, 36, 38, 39, 40, 44, and 45) do not conclusively demonstrate the direction of lateral movement.

As the location of a spillover depends solely on the local topography some streams are diverted into other courses. Figure 4 shows that the relation of distances between streams and lateral displacements can cause apparent inconsistencies. In the case of offset streams the direction of offset indicates the direction of lateral displacement, while diverted streams may or may not indicate the direction of lateral displacement. Analogy and matching sets of streams across the fault will provide a consistent picture.

Fault Ponds (Table 1. Ref. No. 23)

Successive movements across a spur can completely block the drainage, thereby causing a pond. The term "fault pond" is proposed for such features instead of "sag pond", which is sometimes used, as the former indicates more truly the origin and nature of the feature.

Along the Wellington Fault the fault ponds on the upthrow side of the fault can be caused only by lateral displacement.

Trenches (Table 1. Ref. No. 24)

Shallow trenches are common along transcurrent faults. It has been suggested that they are due solely to erosion of fault pug and breccia, but this cannot be maintained because the depth of a trench does not

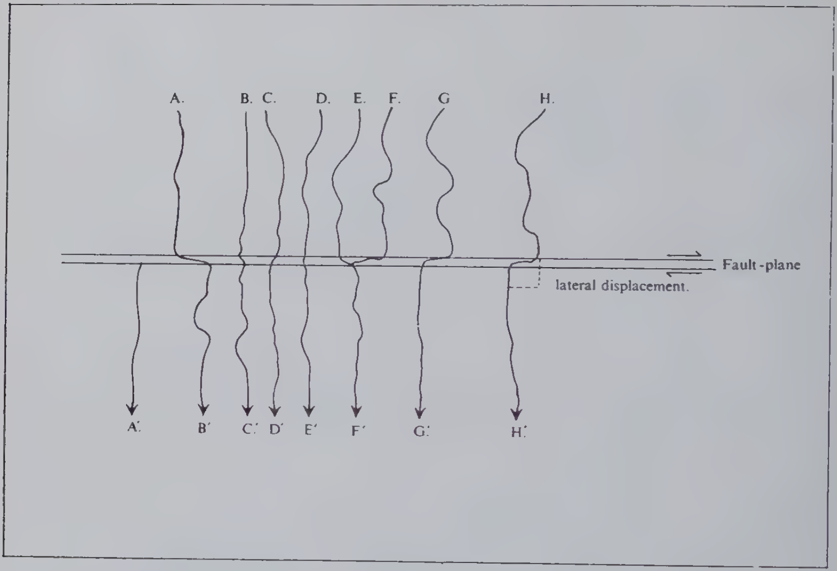

FIG. 4.—Diagram showing offset and diverted streams: Streams A–B′, B–C′, E–F′ indicate apparent anticlockwise (sinistral) displacements because of diversions; streams F–F′, G–G′, and H–H′ indicate clockwise (dextral) displacements; streams F, G, and H are offset streams, and streams A, B, C, D, and E are diverted streams.

change appreciably on rising country. In a breccia zone the trench across a spur should be deeply eroded and on the flat it should be filled by transported material. Their origin is not fully understood but they may be due to superficial subsidence.

Fault Gaps (Table 1. Ref. No. 17)

Notched spurs and saddles between the lateral offset ends of ridge or spur displaced by a transcurrent fault are called fault gaps.

Grabens

Any transcurrent fault is liable to lock if the frictional resistance becomes too great. When this happens a splinter fault with the same transcurrent characteristics commonly develops, thereby relieving the stress built up along the original fault plane. When a transcurrent fault splinters, the area between the faults may lag relative to the areas outside the faults; this results in subsidence of the area between the faults and in the formation of a graben.

DETAILED DESCRIPTION OF SPECIAL LOCALITIES

Table 1 gives the essential particulars for each locality from south to north (Fig. 5). Comments are given below:

Ref. No. 2 and 3: Typical examples of offset streams, which follow the fault trace for the total amount of their lateral displacement and then join the Silver Stream again. A 15 ft scarp extends for 100 yards along the floor of the valley. The scarp has a lower rejuvenated portion about 3 ft high. The Silver Stream is locally entrenched on the upthrow side of the scarp and has cut down in solid greywacke to about 8 ft below the original valley profile.

Ref. No. 4: A good example of diversion.

Ref. No. 5: Lateral displacement has blocked the west-flowing stream, which now follows the fault trace for three-quarters of a mile and ultimately joins the Silver Stream again. The old stream course can still be recognised on the air photos and on the 1:25,000 map (N154/5) as a bush-clad gully, connecting directly with the Silver Stream.

Ref. No. 6 and 7: The saddle between these two localities is a typical fault gap and it is possible that the stream, which now feeds the Karori Reservoirs, was originally a tributary of the Silver Stream. North of the reservoirs any Recent trace of the Wellington Fault has been obliterated by building activities.

Ref. No. 8 and 9: These two shutter ridges in the city of Wellington can be seen on the air photos but are difficult to locate on the ground because of urban development, and they must, therefore, be regarded as uncertain. North from Tinakori Road to Maori Bank (Ref. No. 10) no definite trace of Recent movement has been found. Cotton (1912a) inferred from the absence of wave-cut platforms that the cliffed coast along the Hutt Road is a result of normal faulting. Hall (1946, p. 428), however, recognized a wave-cut platform fronting the fault and interpreted the intensive crushing as evidence for a reverse fault. The sudden decrease in slope of the scarp west of Petone suggests that the Hutt Road scarp has been steepened by cliffing. As the Hutt Road scarp is a retrograded fault scarp, no features along it can be used as evidence of direction (vertical or lateral) of movement along the fault itself, the actual fault being offshore. Farther north the scarp is locally steepened by river undercutting.

Ref. No. 10: This is the nearest known locality north of Wellington where Recent movement can be established. The small total lateral displacement (20 ft) indicates very recent movement, which is confirmed by the small amount of subsequent downcutting.

Ref. No. 11: Emerald Hill (first recognized by H. E. Fyfe) consists of greywacke against which aggradational terraces have been deposited The fault cuts sharply through this hill, but a stream which for some distance occupies the line of faulting, has obliterated any reference surface or line on the east side. Two drainage furrows, however, are clockwise offset by 230 ft.

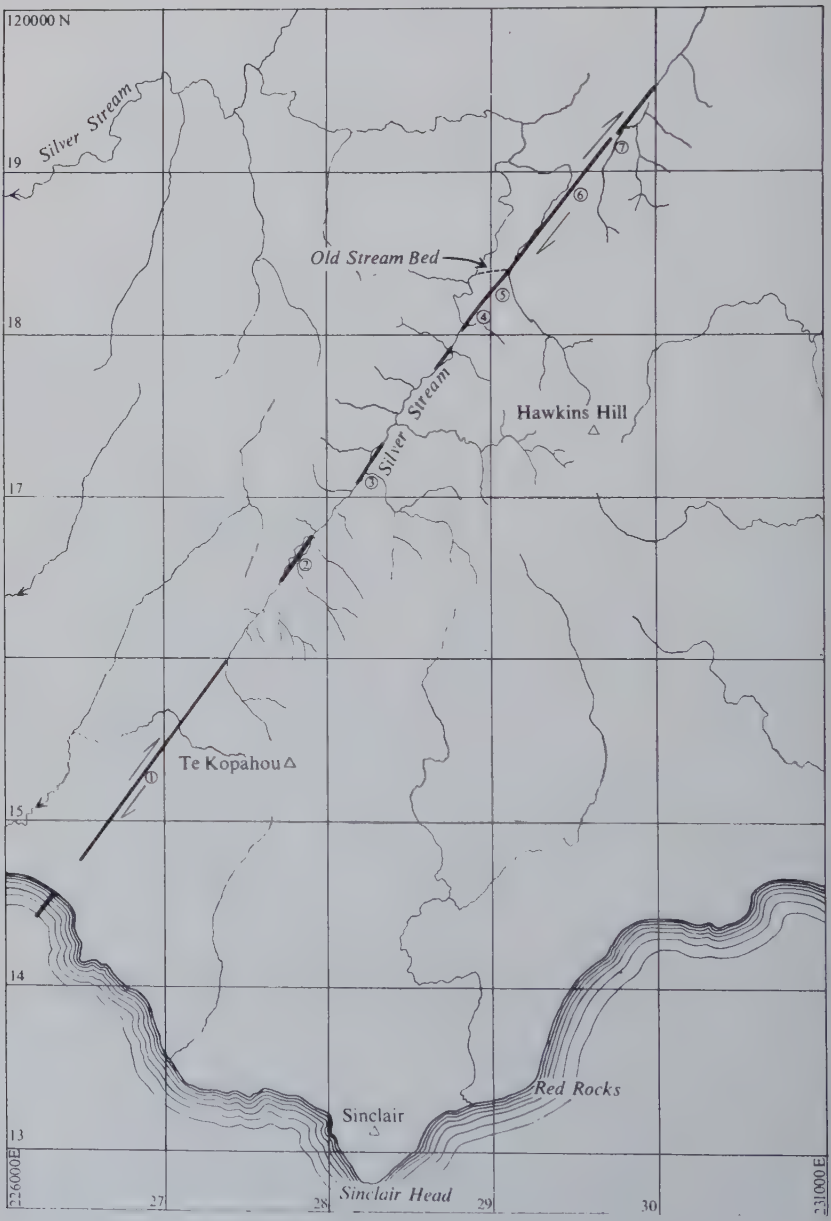

FIG. 5.—Locality map showing the Wellington Fault from the Coast of Cook Strait to the City of Wellington. Reference numbers refer to Table I.

Immediately north of Emerald Hill an example of progressive displacements during terrace downcutting first discovered by Fyfe was re-examined by the writer. Two definite lateral displacements have been established, the time interval between these two movements being represented by 5 ft of river downcutting (Fig. 6). The lowest terraces with a lateral offset of 18 ft show the latest observable displacement (A) along the Wellington Fault, the next two terraces are each offset by a similar amount (B + A = 50 ft).

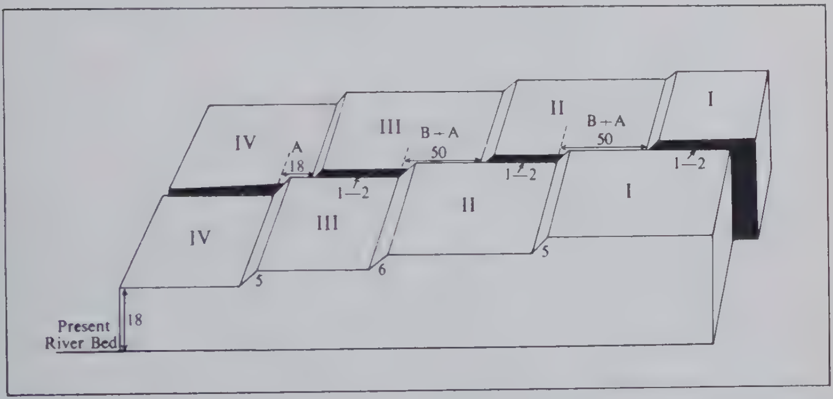

FIG. 6.—Diagram showing progressive faulting during river downcutting just north of Emerald Hill, the faulting occurred in at least 2 stages. Stage A 18 feet, Stage B 32 feet. All measurements are in feet.

During the formation of terrace IV, terrace III has been displaced laterally by 50 — 18 ft = 32 ft. Over the same period the river cut down 5 ft. Since then, terrace IV has been displaced over 18 ft while the river cut down 18ft. If Wellman's assumption of a direct relationship between river downcutting and faulting is valid, the next earthquake to originate along the Wellington Fault would be overdue. Although the 18 ft lateral displacement is the latest observed movement, there may have been later movements, the traces of which have been obliterated. In that case the lateral displacement values of 32 ft and 18 ft for terraces III and IV respectively would have to be reduced by the amount of lateral displacement that has been obliterated.

Ref. No. 13: This is a relatively old feature compared with the 40ft displacement along the fault just south of it (Fig. 7). The area between Tauherenikau River and Mangatainoka River has not completely been covered by air photographs, and where photographed, it is concealed by dense vegetation and, although on air photos features

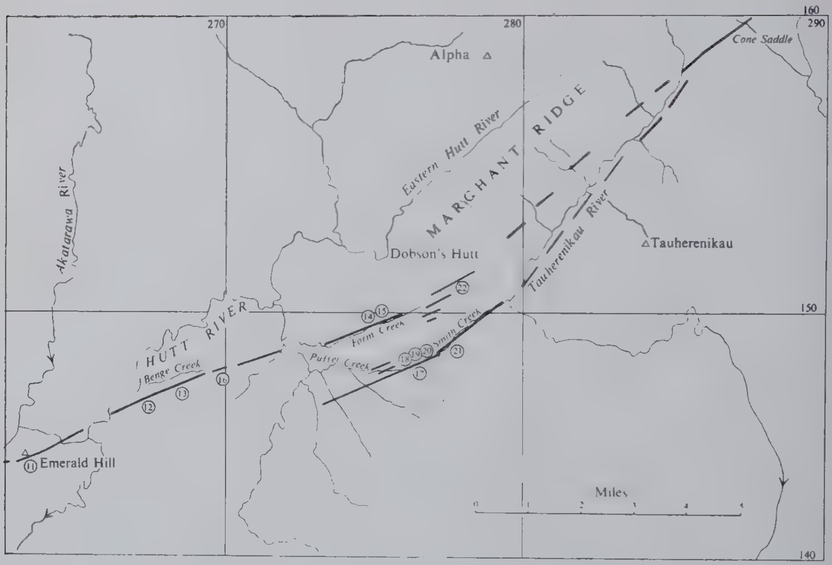

FIG. 7.—Locality map of Wellington Fault between Emerald Hill and Cone Saddle. Reference numbers refer to Table 1.

suggesting tectonic movements can be seen, no definite fault traces have been proved by this method in this area. The straight courses and alignment of the Tauherenikau River, Waiohine River, Totara Creek, Mangatarereatiwhakatu Stream, Waingawa River, Ruapai Stream, and the Mangatainoka River, together with the alignments of saddles between these streams make it reasonably likely that the Wellington Fault continues along these streams. The only reliable air photo interpretation in this area is Ref. No. 23, a series of offset spurs forming fault ponds in two places.

Additional fieldwork by Mr G. W. Grindley and the author has shown that the fault trace follows this alignment. Reference numbers 24 to 34 in Table 1 represent data observed in the field and most of the localities showing recent movement are indicated in Fig. 8. Generally the north-west side of the fault is upthrown, the only exceptions occur along the Ruapai-Mangatainoka ridge where the south-east side is upthrown on two observed traces. The displacement can usually be measured only on spurs and saddles between the rivers. It appears that in the Tararua Range the Wellington Fault consists of series of two parallel faults flanking the valleys.

Along the Wellington Fault belt spilitic lava and tuff (Red Rocks) appear to be associated with the autoclastic breccia (Reed, 1957). In general the sequence across the fault is fault breccia, autoclastic breccia, red rocks, and greywacke.

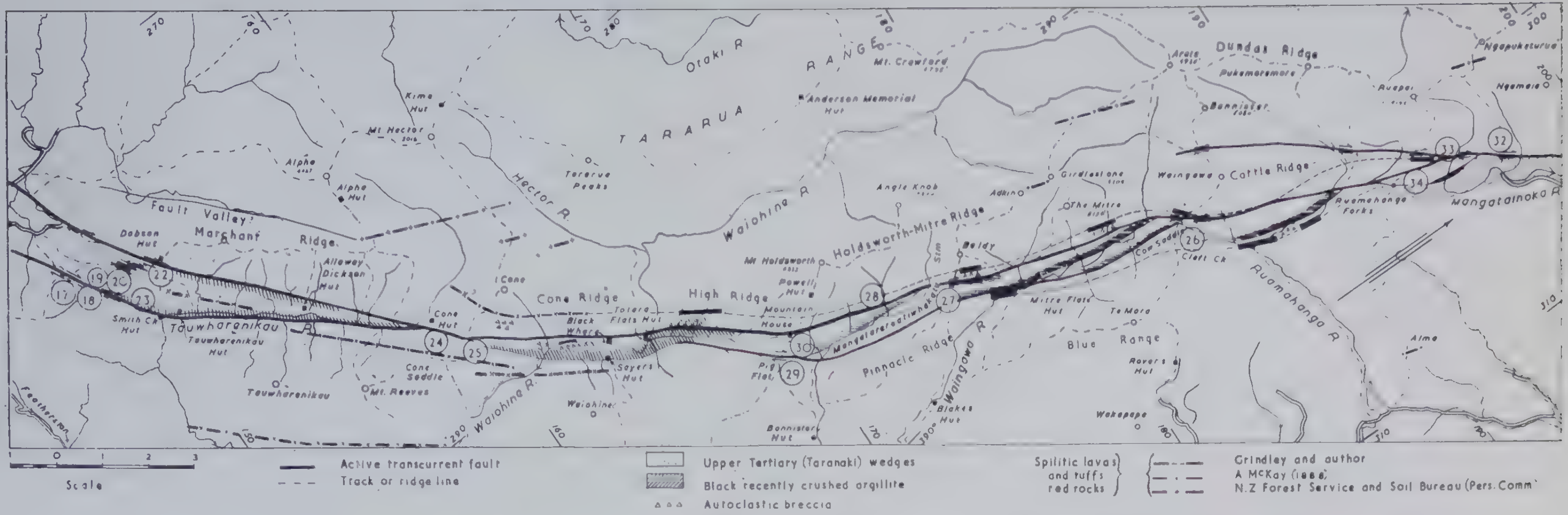

Fig. 8.—Geological map of Wellington Fault between Kaitoke and Mangatainoka River. Reference numbers refer to Table 1

At the Mangatainoka River the Wellington Fault leaves the Tararaus and hugs the eastern flank of this range to Manawatu Gorge. References 35 to 56 are along a continuous trace consisting of displaced spurs, river terraces, and offset streams. The extensive high-level aggradational terrace has been cut down by the meandering Mangahao River, leaving but small remnants that are too small to show any progressive faulting.

Horizontal Displacement

All known horizontal or lateral displacements along the Wellington Fault are clockwise (dextral).

The displacements can be arranged in the following groups in order of magnitude of displacement:

1. Flood plains	25 to 75 ft.
2. Minor spurs, gullies, and saddles	100 to 170 ft.
3. River terraces	150 to 300 ft.
4. Spurs, intervening minor streams	200 to 300 ft.

Where the total lateral displacement is distributed along splinter faults (Fig. 7), the sum of the lateral displacements is about 250 ft, which places it in group 4 of the above list.

The spurs of group 4 and the aggradational terraces of group 3 show substantially the same lateral displacement and must, therefore, be about the same age. The terrace alluvia are considered to be formed by aggradation during the final stage of the last glaciation (Wellman, 1955a). If this is correct, spurs with the same lateral displacement as the terraces must, therefore, have been formed during that cold period. Cotton, 1954b, showed that the Wellington topography has been modified by solifluxion at the close of the last glaciation. It seems, therefore, likely that these spurs have been shaped by solifluxion. The end of the period of solifluxion may, therefore, approximately coincide with the end of the period of aggradation .

Saddles or fault gaps show in general a lateral displacement ranging between 100 and 170 ft. There are some saddles, however, which show no lateral displacement at all; good examples are the saddles just south of reference 1 and reference 17. In both cases shutter ridges a few hundred feet away from these fault gaps show considerable displacements (300 ft and 130 ft respectively). These and other saddles showing no displacements are invariably covered by little or no vegetation, while the saddles showing fault displacements are covered by at least reasonably dense vegetation.

It would, therefore, seem that vegetation is the controlling factor in preserving the fault displacements, especially on saddles where, because of their shape, erosion has a bigger influence in modifying the topography. Erosion into the valleys below the saddles will obliterate any lateral displacement across the saddle, while erosion debris from the spurs above the saddle will tend to mask any lateral displacement (Fig. 9).

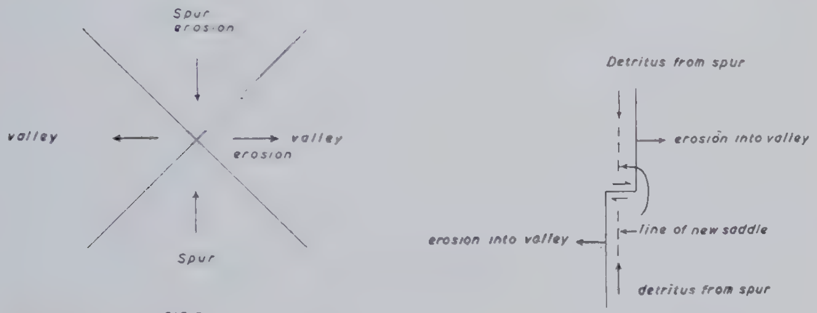

FIG. 9.—(a) Diagrammatic representation of saddle showing the erosional influence. (b) Shows the influence of erosion by cutting back the displaced parts of the saddle resulting in a new saddle.

Comparing the displacements of the saddles with displacements in group 3 and 4, it is evident that the registered movements in the latter groups are approximately twice those in group 2. As features of group 3 and 4 are adjacent to features of group 2, the anomaly in displacements between these groups could indicate that the saddles were devoid of vegetation for considerable time since the first movements took place across features of group 3 and 4, and only the movements which took place after vegetation established itself on the saddles have been preserved.

The post glacial climate was at first boreal with rising temperatures and low humidity (Harris, 1950, 1951) and forest and scrub were apparently confined to the lowlands. As the climate became milder, vegetation covered the lower slopese of the mountains (Lensen, *et al.*, 1956). The timber and scrub lines rose above the saddles and from then on preserved subsequent displacements.

The minor spurs and gullies of this group also show lateral displacements up to 170 ft. Again it would, therefore, seem that previous displacements have not been preserved, and that the flanks of the main spurs, which were covered by solifluxion material, were eroded and dissected to form the minor spurs, until the encroaching vegetation reduced and eventually stopped this process.

Assuming an essentially constant rate of faulting, the actual displacements will date the displaced features relatively to the features showing maximum displacement.

The displacements of features of group 1 will date the relative age of the features which generally consist of the lower river terraces and flood plains.

Both in the Wellington District and in Marlborough most present fault features showing maximum displacement can be regarded as being approximately of the same age (Lensen, in press). Such features showing maximum movement are displaced roughly the same amount. This uniformity in amount of lateral displacement is remarkable.

The rate of faulting along each of these faults seems, therefore, to have been approximately the same since the end of last glaciation. It is difficult to understand why this should be so, unless it is assumed that only a certain amount of strain can be released along any one fault and that a parallel fault or faults will form if the strain increases above this value. The result would be a rather uniform rate of faulting along several transcurrent faults in the same regional stress system.

VERTICAL DISPLACEMENTS

As indicated by the recent movements shown in Table 1, the Wellington Fault is upthrown on the north-west side, the direction of dip changing with change in strike.

With a strike of 40° the fault plane dips steeply towards the north-west, indicating a reverse component; with a strike of 60° it dips towards the south-east, indicating a normal component. The strike of the purely transcurrent fault lies between these strike directions.

The vertical component generally does not exceed 15 ft and is often difficult to measure because of lateral displacement in abruptly changing topography.

EXTENSIONS OF THE WELLINGTON FAULT

North of Manawatu Gorge the Wellington Fault has been followed on air photographs as a continuous trace to Waikaremoana. Along this section the fault bifurcates into several branch faults which all show recent lateral displacements. North of Waikaremoana at least three active branch faults extend into the Bay of Plenty, but due to dense vegetation only one of these branch faults could be traced to the Wellington Fault and further fieldwork will be necessary to link the other branch faults with the main fault.

There is reasonable evidence that the Wellington Fault is the northward extension of the Awater Fault (Lensen, in press) which is a branch fault of the Alpine Fault. The Wellington Fault forms, therefore, part of a New Zealand wide fault pattern.

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SEASONAL VARIATIONS IN SEA-WATER SURFACE TEMPERATURES WITHIN NEW ZEALAND HARBOURS

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Summary

Surface temperature records for the harbours of Auckland, Wellington, Lyttelton, Timaru, Otago, and Bluff have been compiled from observations taken from 1952 to 1955. For certain of these years mean, highest, and lowest recordings for 6-day periods are presented to indicate in some detail the nature of seasonal trends. Monthly means, summer-winter extreme and mean ranges are also tabulated. Diurnal, and abrupt temperature variations in Wellington Harbour are demonstrated and their causes examined. A tidal oscillation in the summer daily temperature anomalies is shown for Portobello (Otago). Seasonal differences between harbour and offshore temperatures at Lyttelton and Otago are outlined. Some ecological implications of widely fluctuating temperatures within harbour waters are discussed. A bibliography of published temperature data for New Zealand ports and harbours is appended.

INTRODUCTION

The increasing interest in marine coastal biogeography in this country emphasizes the need for basic hydrological data. The complex influences of thermal conditions probably exert the greatest limitations to the distribution and dispersal of marine life, and some knowledge of these conditions is fundamental to many studies. As New Zealand lies within temperate latitudes, of particular importance are the seasonal variations which may result in a broad annual range of temperatures at any point of the coastline, and varying geographical positions of isotherms whose values may be critical for the survival or repopulation of species.

Few records of sea-water temperatures and their annual ranges at coastal localities of New Zealand have been published. Most have been set out in terms of monthly means based on a limited number of sporadic observations, and, although adequate for some purposes, tend to be too generalized to be of great value to biological inquiries more intimately concerned with temperature extremes of the physical environment. Over the past four years, more detailed and regular temperature data have been accumulated. These have been compiled for presentation in a form which should supplement existing records and fulfil some of the requirements of the marine littoral ecologist.

These records concern the temperature characteristics within harbours. To varying degrees these waters are partially isolated from those

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off the adjacent coasts and differences in temperature trends arise between them. Comparison of data from several recording methods has made it possible to define the extent of some of these differences and examine some of the characteristics of thermal conditions of the harbour waters themselves.

ORIGIN OF DATA

The methods used in observing temperatures and the localities for which records are tabulated are as follows:

Routine Mercury-thermometer Readings

Surface observations made once daily by immersion of mercury-in-glass thermometers within the harbours of:

Auckland; readings taken at 8.30 a.m. in the vicinity of Calliope Wharf, North Shore, 1954-55.

Wellington; readings taken at 11 a.m. at the Floating Dock Wharf, 1953-55.

Lyttelton; readings taken at 5 p.m. at the Oil Wharf, 1953-55.

Otago; readings taken at 9 a.m. at the Biological Station Wharf, Portobello, 1952-55.

The Auckland, Wellington, and Lyttelton series of observations were made in conjunction with investigations of the seasonal occurrence of marine fouling organisms. Routine observations in Otago Harbour are made by staff of the Portobello Marine Biological Station, University of Otago, and the full series of records since their inception in 1952 has been made available for this compilation through the courtesy of the Director, Dr Elizabeth Batham.

Continuously-recording Thermographs Installed in Ships

Certain vessels operating on coastal and inter-colonial trade routes are equipped with recording instruments to provide supplementary data for surface hydrological surveys. Temperatures are recorded at the vessels' main sea-water injections situated approximately 10 ft below the sea surface. From the resultant thermograms sea temperatures at the various ports of call have been extracted.

ACCURACY

Thermometers used were of reliable quality, reading to 0·1°C. All were checked at N.Z. Oceanographic Institute before use. Ships' thermographs (Negretti & Zambra, mercury-in-steel, 30/90°F) are calibrated from time to time and adjusted if necessary by the staff of the N.Z. Oceanographic Institute. Readings from thermometers are considered to be accurate to within 0·1°C, those from thermographs to within 0·5°C.

PRESENTATION OF TABLES

The precision to which the temperature record of a particular locality may be quoted is obviously limited by the number of observations made during the period concerned, the ideal being represented by the continuous record produced by some permanently installed instrument. The sources outlined above have provided from 1 to 6 readings per day for each port—sufficient detail, it is considered, to indicate the nature of seasonal temperature trends rather more precisely than by compiling monthly means. Accordingly, each calendar month has been divided into five periods, 1st to 6th, 7th to 12th, 13th to 18th, 19th to 24th, 25th to 30th/31st. For each 6-day period, is quoted the *mean* of all temperatures recorded, and the *highest* and *lowest* readings obtained. Means for each calendar month are also tabulated. No value under any category has been included for 6-day periods wherein less than 5 separate readings are available, and monthly means are based on a minimum of 7 readings evenly spaced throughout the month. This treatment has been adopted for records from Auckland (Table 1), Wellington (Table 2), Lyttelton (Table 3), and Otago (Table 4).

The record for Wellington Harbour has been supplemented by the setting up at the Floating Dock Wharf of a recording clockwork thermograph which has been operating since 1 July, 1955. From thermograms it has been possible to extract for successive periods since this date, both the actual *maximum* and *minimum* readings and not only the highest and lowest records of the daily "thermometer" series. Means for each period have been calculated from values at 8 a.m., 4 p.m., and midnight of each day.

Records for the harbours of Timaru (Table 5), and Bluff (Table 6), have been compiled solely from the data of ship-borne thermographs. As there is insufficient information from any one year to tabulate data in the same way as for the four previous harbours, monthly means have been computed from combined values recorded over the years 1952-1955. These, together with highest and lowest recordings for each month, have been included here as an indication of the general range of temperatures to be expected within these two harbours.

SEASONAL VARIATIONS

General Trends

From mid-March until mid-July, mean monthly temperatures at Auckland and Wellington harbours decrease at almost uniform rates of 2·2°C and 1·7°C respectively per month. From early August at Auckland, and mid-August at Wellington, temperatures increase at rates of 1·8°C and 1·5°C per month until mid-December when these rates of increase fall off considerably. In the South Island harbours of Lyttelton and Otago, temperatures commence to fall about mid-February at rates of 2·8°C and 2·0°C per month until the end of June. From the end of July, uniform rates of mean-temperature increase of

2·6°C and 2·2°C per month prevail until mid-December at Lyttelton and early December at Otago.

Ranges between summer and winter temperatures are summarized in Table 7, which includes the highest and lowest monthly means, and extreme individual readings for all harbours. Extreme values given for Timaru and Bluff represent the most reliable available; a greater frequency of observations might well indicate ranges in excess of those noted.

Minimum winter temperatures are generally recorded during July at Auckland, Lyttelton, and Otago, and during August at Wellington. In 1954, however, lowest values at Auckland were not recorded until August. Over the summer, differences in the distribution of highest temperatures have been observed between North Island and South Island localities, maximum values tending to appear at the end of February to early March in the north, and during January in the south. Highest temperatures observed from the four positions from December to March inclusive are plotted in Fig. 1 for the 1953-54 summer. No change in offshore circulation is known that would account for this phenomenon and the effect is most probably one of meteorological consequence.

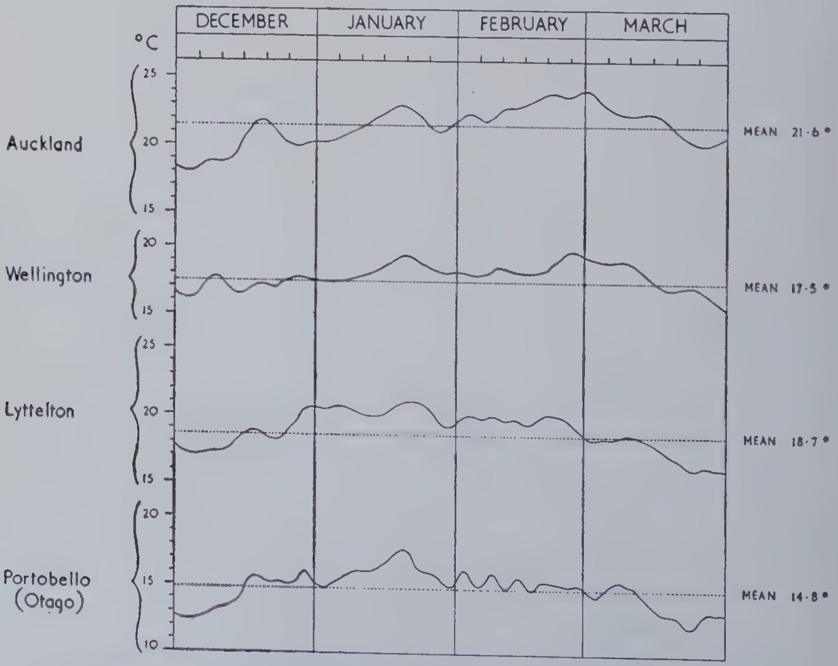

FIG. 1.—Distribution of highest summer temperatures at Auckland, Wellington, Lyttelton, and Otago harbours, 1953-54.

NON-SEASONAL VARIATIONS

Thermograms mechanically recorded at Wellington Harbour show several features worthy of attention in interpreting records based on once-daily thermometer readings. For instance, it appears that at least for the locality in which this instrument is installed, the continuous daily record is seldom of an even, unfluctuating quality. With its sensitive element fixed at a depth of 1½ ft below low spring tide level, the instrument is recording, throughout the tidal cycle, temperatures at depths according to the tidal amplitude which varies from 2·6 ft at neaps to 5·0 ft at springs. For the purposes of this compilation, the layers sampled have been regarded as surface water.

Throughout the series of thermograms, at least two dissimilar characteristics of temperature fluctuation can be recognized:

Irregular Variations

Under this grouping are included the sharp peaks and troughs, traced occasionally on charts about the times of high and low water, particularly during periods of calm weather. As the point of observation is in effect continuously sampling vertically throughout the surface layer, such fluctuations point to the development of stratification. The existence of shallow surface layers of cold fresh water is a likely explanation for sharp drops recorded at low tide, a common occurrence in winter months of 1955. In summer months, sudden rises appearing at low tide indicate the presence of superficial, warm water, while those recorded at high tide suggest the development of a well-marked thermocline. Sudden rises recorded at low water during the 1955-56 summer averaged 4·0°C in magnitude, and drops at low water during the 1955 winter were of the order of 2·0°C. Most took place over a period of about 15 min.

Periodic Variations

The second feature of Wellington thermograms is a slow rise in temperature frequently observed to take place during the daylight hours. This trend usually commences between 8 a.m. and 10 a.m. and after the temperature reaches a maximum between noon and 4 p.m. it falls off to lower levels during the night*. The effect is most pronounced in summer when the rise may be of the order of 4·5°C, and least pronounced in winter when it is just perceptible on the daily chart. The trend is generally restricted in its occurrence to days with clear skies and little wind. Although analysis of further data may subsequently show otherwise, the times corresponding to the rise, peak, and fall do not appear, from present observations, to be dependent on the state of the tide. Temperatures throughout days when wind speeds are consistently greater than some 6 knots tend to be uniform, and apparently the mixing induced by turbulence is sufficient to mask the trend and cause a thermal homogeneity at least over the depth sampled by the instrument. The phenomenon is illustrated in Fig. 2, which is a reproduction of the thermogram for the week 6 to 13 January, 1956. Air temperature, mean hourly wind speeds, hours of sunshine (all from Kelburn Meteorological Station records), and the tidally varying height of water above the instrument have been superimposed on the same chart. The occurrence and magnitude of these daily rises show a high degree of correlation with hours of sunshine as recorded at Kelburn (correlation coefficient, $r = 0{\cdot}75$ at 1% level, based on records taken from 12 consecutive days, 3 to 14 October, each daily rise being assessed by subtracting the 8 a.m. value from the peak temperature). It would seem, therefore, that the trend is an effect of surface heating due to absorption of solar radiation. Daily air temperatures have a similar pattern to those of sea temperatures, peak values of which follow those of air temperatures by a short time lag.

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*Early instances of daily temperature rise aroused suspicion of an instrument error that might possibly be caused by direct solar heating of the exposed 10 ft of capillary line between sensitive element and recorder, in spite of insulation offered by the coaxial enclosing sheaths of asbestos, copper and lead. The "capillary error" of the instrument, however, is quoted by the manufacturers (Negretti & Zambra) as 1/10 of 1% of the scale range; that is, for a 10°C change in temperature of the capillary, an error of only 0·03°C is introduced to the reading.

A laboratory check was also made with two identically calibrated instruments, each of whose elements was submerged in a water tank. The capillary line of one was led under a bench and well insulated with cotton waste, while the second capillary was reeled behind a large window fully exposed to afternoon sun. A week's running in clear fine weather failed to show any disparity between the two thermograms.

A notable characteristic of sea-water temperature records from Portobello (Otago Harbour) is a frequent day-to-day variation in readings. This is most pronounced during summer months. An investigation was made of the possibility of a relationship between these variations and the tidal cycle, and since observations were made at the same time each day a similar method was used to that adopted by Proudman (1943), for salinity variations in the Irish Sea. Daily temperature anomalies were calculated over the four-month period, December 1953 to March 1954, by subtracting the appropriate monthly mean fom each daily reading. These anomalies were then arranged in twelve groups at hourly intervals from the predicted time of high tide at Portobello*. From the mean anomaly for each group was subtracted the overall mean, and the results are set out in Table 8. A regular variation in these mean anomalies can be seen and this is interpreted as being a tidal effect on the daily anomalies. On the basis of predicted tide tables, temperatures over the four months considered are, on the average, slightly over 1·0°C higher just after low tide than in the hour following high tide. As Otago Harbour is predominantly shallow, this tendency would be consistent with the warming of water

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*Predicted times of high water at Dunedin from N.Z. Nautical Almanac and Tide Tables, 1953/54. Batham (1956) reported that low tide at Portobello is usually about 35 min. in advance of the predicted time of low water at Dunedin. For the present calculations, the time of high tide at Portobello has been assumed to be ½ hr earlier than at Dunedin.

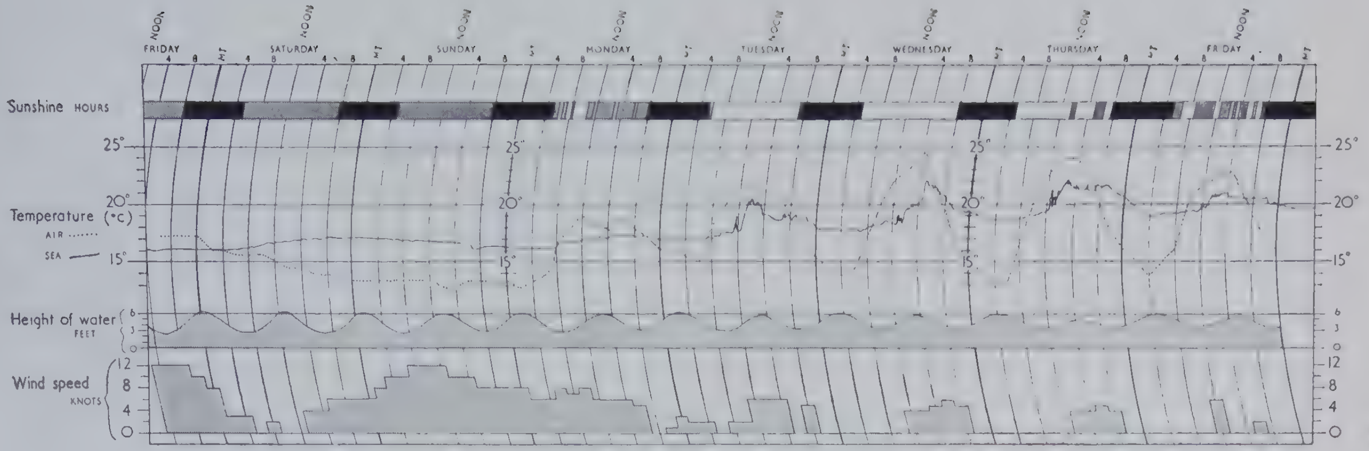

FIG 2.—Thermogram for the week, 6 to 13 January, 1956, at Wellington Harbour. Air temperature, sunshine, wind speed, and tide records have been superimposed to illustrate the influences of solar radiation and wind on sea adn air temperatures. In the sunshine record, clear sky is represented by a blank space, overcast sky by diagonal shading, and hours of darkness by solid shading.

on the flood tide as it engulfs areas of sand-banks which have been directly exposed to solar radiation during the period of low water.

COMPARISON WITH OFFSHORE TEMPERATURES

In summer months, surface temperatures within Lyttelton and Otago harbours are appreciably higher than those of waters offshore. Both basins enclose large areas of shallow water and the effect of solar radiation as discussed above for Otago most probably applies to Lyttelton as well. In winter, temperatures tend to be lower within the basins, possibly due to combined effects of increased influx of cold, fresh water, low air and ground temperatures, and general atmospheric cooling. In either case, the differences are readily detected by the recording thermographs of ships entering and leaving port. Seasonal disparities between harbour and offshore temperatures for Lyttelton and Otago are shown in Table 9. Where available, averaged values, expressing the amount by which temperatures in the harbours exceed or fall short of those offshore, are given for each month. The offshore point of reference for Lyttelton was selected at 1 mile north of Godley Head, that for Otago, at 1 mile north of Taiaroa Head.

Comparisons are not given for Auckland, for ships' thermographs record little change in surface temperature between western Hauraki Gulf waters and those in the vicinity of the main wharves. It is to be expected that at Auckland there will be freer exchange and more efficient tidal mixing between lower harbour and offshore waters than at Lyttelton and Otago. In Wellington the relationship is difficult to assess from thermograms because of the great variability in surface temperatures of water immediately beyond the harbour entrance. At Timaru and Bluff, where there is relatively free intercommunication between harbour and offshore waters, differences in temperature have not been observed.

DISCUSSION

To what extent both the development of stratification and the diurnal rise in temperature as observed in Wellington Harbour may be common to all areas of the Harbour's surface waters cannot be deduced from the limited evidence outlined here. The brief persistence of abrupt temperature changes suggests that here they arise in thin surface layers only. Such thin layers may be confined to the more shallow (or sheltered) peripheral areas such as that sampled, which are nearer to the influences of land drainage and ground temperatures. On the other hand, an indication that deeper layers of surface water (i.e. greater than the sampled depth) undergo a diurnal change in temperature is shown by the lack of an immediately apparent tidal effect in the recordings. Although the initial heating of these surface waters may have predominated in shallow areas, it is to be expected that the larger volumes of water will enter wider circulation. However surface waters of varying temperatures are dispersed throughout a harbour, it is evident that a system of once-daily thermometer readings is likely to fail to detect details of quick temperature changes that may contribute to a much wider thermal spectrum, either from day to day, or from season to season.

The biological importance, to marine forms, of widely fluctuating temperatures in their permanent regime is a subject which awaits the necessarily intensive investigation. It is interesting to reflect, however, that the diurnal rise of 4°C in surface waters at Wellington Harbour on 1/10/55 is equivalent in magnitude to the range between monthly means for August and November (i.e. mid-winter and late spring). Relatively sudden increases of this sort may not be without far-reaching effects among the multitude of biochemical reactions contributing to the various physiological processes. One consequence at the survival level may result in the natural selection of organisms of wide eurythermal capacities. Another situation may arise whereby a succession of peak temperatures of sufficient intensity may act as trigger temperatures in the induction of spawning, metamorphosis, and other phases of the life cycle.

A seasonal differential heating or cooling of harbour waters might be expected to influence the geographical distribution of species in a manner discussed by Hutchings (1947) as a variant of seasonally extended distribution. For instance, a species whose permanent range is equatorward of Wellington, may have a motile stage whose survival tolerance is wide enough to permit southward dispersal to Wellington Harbour waters, where peak summer temperatures are at a sufficiently high level to support metamorphosis or even the temporary establishment of a vegetative phase. Thus might arise a pocket distribution, similar to Hutching's category of a fringe population, maintained by larval infiltration from the permanent range. A converse situation for poleward species may arise in winter when harbour temperatures (viz. Lyttelton and Otago) are lower than those offshore and therefore akin to those prevailing at some southern centre of dispersal.

As no records have been made, it is not known whether the fluctuating nature of harbour temperatures as shown in Wellington are characteristic of shallow waters adjacent to open coasts. The influences of solar radiation will be similar but it is to be expected that through wave action, surface waters will tend to be isothermal. Maxwell (1956) considered that temperature differences between Wellington Harbour and offshore waters are insufficient to be regarded as a limiting factor for eurythermal animals of the shelf area beyond the harbour entrance which do not normally populate the harbour. Maxwell's records were based on once-weekly to fortnightly thermometer readings, an inadequate frequency to detect short-period fluctuations which may, in fact, be well outside the eurythermal capacity of the shelf forms. This author's further postulation that differences between surface and bottom temperatures in Wellington Harbour are at the most, 2°C is not borne out by thermograph records wherein 4°C differences have frequently been observed within the uppermost 6 ft of water.

Large variations in sea temperature along the coast of southern California have been observed and investigated by Arthur (1954) and by Leipper (1955). Changes of up to 5°C in the temperature of water near the bottom were found to be nearly periodic; they occurred only during the summer months when surface layers were highly stratified, and were more marked in shallow inshore waters than in those beyond the coast. These changes were found to arise from the periodic migration of cold spots which Leipper considered developed over shallow regions of irregular bottom by variations in velocity of tidal current. Arthur suggested that the oscillations of cold regions might be associated with internal waves. These temperature variations, Arthur observed, must represent considerable changes in the nearshore biological environment, shallow water benthic forms experiencing during a single summer's day abrupt changes as great as the seasonal changes. If a similar development of cold spots were to be detected in the coastal vicinity of Wellington, Lyttelton, and Otago harbours, for instance, it is possible that, between harbour and open coast waters, the thermal disparity may be even greater in summer than could be accounted for by solar radiation effects in the sheltered basins alone.

Acknowledgements

Grateful acknowledgement is made for recording temperatures in Auckland Harbour to the staff of the Draughting Section, Naval Dockyard; in Wellington Harbour to Mr J. Anderson, Dock Foreman, Wellington Harbour Board; and in Lyttelton Harbour to Lieutenant (S) A. Lambert, R.N.Z.N., formerly Officer-in-Charge, H.M.N.Z.S. "Tasman". For making available temperature records from Otago Harbour, thanks are expressed to Dr E. J. Batham, Director of the Portobello Marine Biological Station, University of Otago, and to her staff who undertake the regular observations. Mr Neal Utting, technician, N.Z. Oceanographic Institute, gave valuable assistance in the compilation of data.

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TABLE 1.—Auckland Harbour, Sea-surface Temperature Record, 1954-1955.

Period		1954				1955			
		Mean	Hghst. recording	Lowest recording	Mean for month	Mean	Hghst. recording	Lowest recording	Mean for month
Jan.	1– 6					20·2	20·3	20·0	
	7–12								
	13–18				21·6	22·4	22·8	21·7	21·5
	19–24					22·3	23·3	21·5	
	25–31					21·1	21·4	20·6	
Feb.	1– 6					22·2	22·8	21·9	
	7–12					22·3	22·8	21·7	
	13–18	21·8	22·0	21·6	22·1	23·2	23·6	22·8	23·1
	19–24	22·3	23·1	21·6		23·7	24·4	23·3	
	25–28	22·2	22·2	22·2		23·9	24·2	23·6	
March	1– 6	22·1	22·5	21·4		22·9	24·0	21·7	
	7–12	21·0	21·4	20·5		22·4	23·2	22·2	
	13–18	20·7	21·2	20·3	21·0	21·8	22·5	21·1	21·7
	19–24	21·0	21·1	20·8		20·4	21·0	20·0	
	25–31	20·1	20·6	19·1		20·6	20·8	20·3	
April	1– 6	18·5	20·2	18·0		21·0	21·1	20·8	
	7–12	18·2	18·6	17·7		20·7	20·8	20·6	
	13–18	18·0	18·7	17·5	17·6	20·4	20·6	20·2	20·1
	19–24	17·7	18·0	17·5		20·1	20·3	19·4	
	25–30	15·8	16·3	15·5		18·5	19·0	17·8	
May	1– 6	15·8	16·5	15·5		17·5	17·8	17·2	
	7–12	15·9	16·1	15·8		17·7	18·1	17·2	
	13–18	16·3	16·6	16·1	15·7	17·1	17·5	16·7	16·9
	19–24	15·5	16·4	14·7		16·4	17·2	15·8	
	25–31	15·0	15·3	14·7		15·7	16·1	15·6	
June	1– 6	14·8	15·0	14·7		15·3	15·6	14·4	
	7–12	15·1	15·3	14·7		13·7	13·9	12·8	
	13–18	14·6	15·0	14·4	14·1	13·2	13·5	12·8	13·3
	19–24	13·5	13·8	13·3		12·6	12·8	12·2	
	25–30	12·4	13·3	10·5		11·7	11·7	11·7	
July	1– 6	12·2	13·0	11·1		11·6	11·9	11·1	
	7–12	12·4	12·8	11·1		11·5	11·7	11·1	
	13–18	11·7	12·5	11·4	12·2	10·8	11·1	10·6	11·3
	19–24	12·4	12·8	11·9		11·5	11·7	11·1	
	25–31	12·3	12·5	12·2		11·2	11·7	10·6	
Aug.	1– 6	11·4	12·0	10·5		11·8	11·9	11·7	
	7–12	10·0	11·4	8·7		12·2	12·5	11·7	
	13–18	11·4	11·4	11·4	11·4	12·5	12·8	12·2	12·1
	19–24	11·8	12·0	11·6					
	25–31	12·4	12·5	12·2					
Sept.	1– 6	12·2	12·5	11·9					
	7–12	12·7	12·7	12·5					
	13–18	13·1	13·3	12·7	13·1				14·0
	19–24	13·9	14·1	13·6					
	25–30	13·8	14·1	13·6					
Oct.	1– 6	14·2	14·4	13·9					
	7–12	15·3	15·4	15·0					
	13–18	14·9	15·0	14·7	15·2				15·0
	19–24	15·7	15·8	15·5					
	25–31	16·0	16·1	15·8					
Nov.	1– 6	17·0	17·2	16·7					
	7–12	18·9	20·0	18·3					
	13–18	19·2	19·4	18·9	18·5				17·6
	19–24	18·9	19·4	18·3					
	25–30	18·4	19·4	17·5					
Dec.	1– 6	18·3	18·6	17·8					
	7–12	18·7	18·9	18·3					
	13–18	20·1	21·1	19·2	19·6				20·0
	19–24	21·1	21·7	20·6					
	25–31								

TABLE 2.—Wellington Harbour Sea-surface Temperature Record, 1953–1955.

	1953				1954			
Period	Mean	Hghst. recording	Lowest recording	Mean for month	Mean	Hghst. recording	Lowest recording	Mean for month
Jan. 1– 6				16·0	17·4	17·6	17·2	17·4
7–12					17·1	17·5	16·7	
13–18					17·0	17·1	16·9	
19–24					17·8	18·3	17·2	
25–31					17·9	18·3	17·8	
Feb. 1– 6				17·1	17·7	18·1	17·2	17·5
7–12					17·0	17·1	16·9	
13–18					17·0	17·5	16·4	
19–24					17·8	18·1	17·5	
25–28					18·6	18·9	18·3	
March 1– 6				16·5	18·2	18·6	17·8	17·7
7–12					17·6	17·8	17·5	
13–18					17·5	17·6	17·2	
19–24					17·5	17·6	17·5	
25–31					17·3	17·5	16·9	
April 1– 6				15·2	15·3	15·8	15·0	14·4
7–12					14·5	14·8	14·2	
13–18					14·3	14·4	14·2	
19–24					14·3	14·4	14·2	
25–30								
May 1– 6				13·8	12·7	13·2	12·8	12·9
7–12					12·9	13·3	12·7	
13–18					13·3	13·7	12·7	
19–24					12·8	13·0	12·5	
25–31					12·4	12·5	12·3	
June 1– 6				12·4				12·2
7–12								
13–18								
19–24								
25–30								
July 1– 6				11·0				10·5
7–12								
13–18								
19–24								
25–31								
August 1– 6	9·9	11·1	8·6	10·4	10·9	12·2	9·5	9·6
7–12	9·9	10·0	9·7		8·8	9·3	8·5	
13–18	10·6	10·8	10·3		8·9	9·0	8·7	
19–24	10·6	10·7	10·6		9·1	9·3	8·9	
25–31	10·9	11·1	10·6		10·2	11·1	9·4	
Sept. 1– 6				12·0	9·4	9·5	9·2	11·0
7–12	11·9	12·2	11·7		10·0	10·3	9·7	
13–18	11·8	12·2	11·4		10·5	10·8	10·2	
19–24	12·1	12·5	11·9		11·7	12·7	10·5	
25–30	12·4	12·5	12·2		12·0	12·7	11·4	
Oct. 1– 6	12·0	12·0	11·9	12·5	12·8	13·3	11·7	13·1
7–12	12·0	12·3	11·5		12·8	13·4	12·2	
13–18	12·4	12·8	12·2		12·8	13·3	12·2	
19–24	12·9	13·2	12·6		13·7	14·4	13·3	
25–31	13·2	13·3	13·1		13·5	14·4	13·1	
Nov. 1– 6	14·2	14·4	14·0	14·9	14·4	14·4	14·4	15·2
7–12	14·6	14·7	14·4		15·0	15·6	14·2	
13–18	14·7	15·0	14·5		15·5	16·1	15·0	
19–24	15·2	15·3	15·0		15·4	15·6	14·4	
25–30	15·9	16·4	15·6		15·7	16·7	14·6	
Dec. 1– 6	16·0	16·2	15·6	16·5	16·2	16·6	15·7	16·7
7–12	17·2	17·8	16·4		16·7	17·7	16·1	
13–18	16·5	16·9	16·3		17·1	19·4	15·7	
19–24	16·4	16·7	16·1		16·7	17·7	16·1	
25–31	16·3	16·4	16·1		17·2	17·7	16·2	

TABLE 2.—*Continued.*

1955

Mean	Hghst. recording	Lowest recording	Mean for month
17·3	18·3	16·6	17·8
17·6	18·3	17·2	
17·6	18·3	17·2	
19·4	20·0	18·3	
17·6	18·3	16·4	
17·4	18·3	16·6	17·8
17·8	18·8	16·9	
17·6	18·3	16·3	
18·1	18·8	17·6	
18·1	20·0	15·6	
18·4	19·4	17·2	17·4
18·3	19·4	17·2	
17·3	18·3	16·4	
16·6	17·7	15·8	
15·9	17·7	15·3	
15·6	15·7	15·5	15·2
15·3	15·6	15·0	
15·6	15·7	15·4	
15·4	15·6	15·1	
14·5	15·0	13·9	
13·5	13·6	13·3	13·8
14·0	14·4	13·9	
13·9	13·9	13·9	
13·9	13·9	13·9	
			12·3
8·8	9·7*	7·4†	8·8
9·0	10·3	6·7	
8·9	9·4	7·9	
8·8	9·2	8·4	
8·6	9·5	7·3	
9·3	10·2	8·7	10·2
10·0	10·5	9·3	
10·3	10·7	9·3	
10·4	11·0	9·4	
10·8	11·3	10·4	
10·5	11·0	8·5	10·9
10·5	11·2	9·3	
10·6	11·7	9·9	
11·3	12·1	10·5	
11·7	12·8	10·1	
13·2	14·4	11·8	13·2
13·5	16·4	12·1	
12·9	14·1	12·0	
13·1	14·4	12·5	
13·5	15·1	12·7	
13·6	14·7	13·0	14·4
14·2	15·6	13·3	
14·4	15·7	14·0	
14·8	16·5	14·2	
15·1	16·3	14·6	
15·4	16·0	14·9	16·7
16·4	18·2	14·5	
17·1	20·6	15·8	
17·5	19·9	16·4	
17·1	18·4	15·5	

*From 1 July, maximum

†From 1 July, minimum

TABLE 3.—Lyttelton Harbour, Sea-surface Temperature Record, 1953–1955.

Period	1953				1954			
	Mean	Hghst. recording	Lowest recording	Mean for month	Mean	Hghst. recording	Lowest recording	Mean for month
Jan. 1– 6					18·8	19·7	17·8	19·1
7–12					18·7	19·7	18·1	
13–18					18·6	19·2	17·8	
19–24					19·6	20·3	18·9	
25–31					19·7	20·8	19·2	
Feb. 1– 6					19·8	20·3	19·2	19·5
7–12					19·4	20·3	18·3	
13–18					19·3	20·3	18·5	
19–24					19·2	19·7	18·6	
25–28					19·8	20·4	19·2	
March 1– 6					19·6	20·0	18·9	17·7
7–12					17·7	18·6	17·0	
13–18					17·7	18·5	16·7	
19–24					17·3	18·0	16·2	
25–31					16·0	16·5	15·0	
April 1– 6					14·5	15·0	13·9	14·0
7–12					14·6	15·0	13·9	
13–18					14·1	14·5	13·6	
19–24								
25–30								
May 1– 6								11·9
7–12					12·2	12·2	12·2	
13–18					12·0	12·2	11·7	
19–24					12·0	12·2	11·7	
25–31					11·6	11·7	11·1	
June 1– 6					11·1	11·4	10·8	9·8
7–12					10·7	10·8	10·6	
13–18					10·1	10·4	9·4	
19–24					9·0	9·4	8·4	
25–30					8·0	8·3	7·8	
July 1– 6					7·8	8·3	7·5	7·2
7–12					6·9	7·5	6·1	
13–18					6·7	6·9	6·1	
19–24					7·4	7·8	7·2	
25–31					7·1	7·5	6·5	
Aug. 1– 6	8·0	8·1	7·2	8·1	7·1	7·2	6·7	7·7
7–12	8·0	8·2	7·8		7·3	7·8	6·4	
13–18	8·1	8·3	8·0		7·6	8·3	7·2	
19–24	8·2	8·2	8·2		8·2	8·9	7·7	
25–31	8·5	8·9	8·2		8·5	9·2	8·1	
Sept. 1– 6	9·7	10·6	8·7	10·2	8·2	8·9	7·8	10·0
7–12	10·3	11·1	10·0		8·9	10·0	8·1	
13–18	10·4	10·6	10·0		10·2	11·1	8·9	
19–24	11·3	12·2	10·2		10·9	12·2	10·0	
25–30	11·4	11·9	10·6		11·8	12·8	10·8	
Oct. 1– 6	10·8	11·8	10·2	12·4	12·7	13·9	11·7	13·4
7–12	11·2	12·2	10·3		13·7	14·4	12·8	
13–18	12·3	12·8	11·1		13·0	13·9	12·5	
19–24	13·2	14·4	11·4		13·3	13·9	12·5	
25–31	14·5	15·0	14·1		14·3	15·3	13·6	
Nov. 1– 6	15·4	15·8	15·3	15·7	15·2	16·4	14·4	16·2
7–12	15·6	16·4	14·9		15·6	16·9	14·9	
13–18	14·6	15·8	13·9		16·7	17·8	15·6	
19–24	16·0	16·9	15·3		16·8	17·8	16·1	
25–30	17·0	18·1	15·8		16·8	17·5	16·4	
Dec. 1– 6	17·9	18·6	16·8	17·3	17·0	17·8	16·5	17·9
7–12	17·2	18·1	16·1		16·9	17·8	16·3	
13–18	17·5	18·6	16·7		17·9	18·9	16·5	
19–24	16·5	17·5	15·8		18·1	18·9	17·4	
25–31	17·3	18·1	16·3		19·7	20·6	18·3	

TABLE 3.—*Continued.*

1955			
Mean	Hghst. recording	Lowest recording	Mean for month
20·2	20·6	20·0	19·9
20·1	20·6	19·4	
19·8	20·6	18·9	
20·3	21·1	19·4	
19·4	20·5	18·6	
19·4	20·3	18·5	19·3
19·4	20·0	18·9	
19·1	20·6	18·1	
19·5	20·6	18·5	
18·9	19·4	18·3	
18·0	18·3	17·2	17·2
18·3	19·2	17·8	
17·4	18·3	16·1	
16·2	17·2	15·3	
16·2	17·2	15·0	
16·6	17·2	15·8	15·2
16·1	16·7	15·3	
15·6	16·4	15·0	
14·7	15·6	13·9	
13·7	16·1	12·8	
11·8	12·2	11·1	11·9
12·2	12·8	11·4	
12·2	13·1	11·7	
12·0	12·8	11·7	
11·2	11·7	10·8	
10·6	11·4	10·0	9·0
9·3	10·0	8·9	
8·7	9·4	8·5	
8·0	8·3	7·8	
7·6	8·3	7·2	
7·4	7·8	7·2	7·4
7·3	7·5	6·9	
6·9	7·2	6·7	
7·5	7·8	7·2	
7·7	8·1	7·2	
7·9	8·3	7·8	8·6
8·5	8·6	8·3	
8·7	8·9	8·6	
8·6	9·2	8·3	
9·5	10·6	8·9	
12·6	12·8	12·4	13·4
13·3	13·8	12·8	
14·1	14·4	13·9	
13·0	13·2	12·7	
14·2	14·5	14·0	
16·5	16·7	16·1	16·4
16·1	16·3	15·6	
16·5	16·9	16·3	
16·5	16·9	16·3	
17·0	17·3	16·6	18·0
18·3	18·2	18·4	
18·1	18·9	17·3	
18·4	19·0	17·9	
17·6	18·4	17·2	

TABLE 4.—Portobello (Otago Harbour), Sea-surface Temperature Record, 1952–55.

		1952				1953			
Period		Mean	Hghst. recording	Lowest recording	Mean for month	Mean	Hghst. recording	Lowest recording	Mean for month
Jan.	1– 6					16·1	17·3	14·6	16·1
	7–12					16·8	17·9	14·8	
	13–18					15·8	16·4	15·0	
	19–24					16·0	17·2	14·5	
	25–31					15·8	17·0	14·8	
Feb.	1– 6					15·9	16·9	15·1	15·1
	7–12					17·6	18·4	16·6	
	13–18					14·3	15·3	13·5	
	19–24					13·2	13·6	12·8	
	25–28					13·9	15·6	13·3	
March	1– 6					14·0	14·8	13·5	13·3
	7–12					14·4	14·7	14·1	
	13–18					12·4	13·5	11·6	
	19–24					13·2	13·6	12·5	
	25–31					12·4	14·1	11·1	
April	1– 6					11·6	12·0	10·9	10·7
	7–12					10·7	11·6	9·5	
	13–18					10·2	10·9	9·8	
	19–24					10·4	11·0	9·5	
	25–30					10·6	11·0	10·2	
May	1– 6					10·7	10·8	10·5	8·9
	7–12					10·0	10·8	8·5	
	13–18					8·0	8·5	7·5	
	19–24					7·8	8·4	7·2	
	25–31					8·2	8·7	7·9	
June	1– 6					8·5	8·9	8·0	7·2
	7–12					7·1	7·8	6·8	
	13–18					7·6	7·8	7·2	
	19–24					6·5	6·8	6·0	
	25–30					6·0	6·4	5·5	
July	1– 6	5·5	5·9	5·2	5·8	6·8	7·0	6·6	6·1
	7–12	5·6	5·7	5·5		6·2	7·2	5·2	
	13–18	5·6	5·9	4·8		5·6	6·0	5·4	
	19–24	6·1	6·3	5·9		5·8	6·4	5·2	
	25–31	6·2	6·6	5·9		6·2	6·4	5·8	
Aug.	1– 6	6·5	6·6	6·1	7·6	6·8	7·4	6·4	7·3
	7–12	6·7	7·7	5·9		7·1	7·5	6·8	
	13–18	7·8	8·2	7·4		7·5	8·0	6·9	
	19–24	7·9	8·2	7·5		6·9	7·2	6·5	
	25–31	8·9	9·4	8·3		8·0	9·4	7·2	
Sept.	1– 6	8·9	9·1	8·8	9·7	9·7	10·1	9·2	9·3
	7–12	9·4	9·8	9·0		9·0	9·5	8·4	
	13–18	10·4	10·9	10·0		9·0	9·9	8·1	
	19–24	10·3	10·9	9·5		10·5	10·9	10·0	
	25–30	9·7	10·4	8·9		8·5	10·5	7·0	
Oct.	1 - 6	10·8	11·6	10·1	11·8	8·6	9·2	7·5	11·1
	7–12	11·2	11·7	10·5		9·6	10·5	8·8	
	13-18	12·5	13·4	11·1		11·2	11·5	11·0	
	19–24	11·7	12·2	11·1		12·3	13·5	11·5	
	25–31	12·6	13·4	11·8		13·2	14·0	12·4	
Nov.	1– 6	12·4	12·9	12·1	12·8	13·6	14·5	12·8	13·4
	7–12	11·8	12·5	10·9		13·0	13·8	12·5	
	13–18	12·9	13·8	11·0		12·8	13·5	12·2	
	19–24	12·9	13·7	12·1		13·0	14·0	11·6	
	25–30	14·0	14·5	13·5		14·4	15·0	13·4	
Dec.	1– 6	14·3	14·6	14·0	15·9	15·2	15·8	14·3	14·7
	7–12	14·8	15·3	14·3		13·8	14·7	13·1	
	13–18	16·0	16·8	14·5		15·0	15·5	14·4	
	19–24	16·0	16·5	15·6		14·1	14·8	13·6	
	25–31	18·0	18·6	17·1		15·1	15·9	14·6	

TABLE 4.—*Continued.*

1954				1955			
Mean	Hghst. recording	Lowest recording	Mean for month	Mean	Hghst. recording	Lowest recording	Mean for month
16·2	17·4	15·2	15·6	14·8	15·2	14·5	15·8
14·8	15·8	13·8		16·0	16·6	15·8	
14·8	16·4	14·1		16·6	17·5	15·9	
16·2	16·5	15·7		17·0	17·8	15·9	
16·0	17·2	14·8		14·6	16·3	12·5	
16·1	16·8	15·0	15·9	15·1	16·7	14·0	15·2
15·0	16·5	13·7		15·3	16·4	14·7	
16·2	16·4	15·8		15·2	16·1	14·6	
16·0	16·5	15·4		15·3	15·5	14·9	
16·5	16·9	15·4		15·3	15·4	15·0	
16·1	16·5	15·8	14·8	14·7	15·9	13·8	13·8
14·5	16·4	13·2		15·2	15·7	14·5	
15·1	15·4	14·8		13·3	14·2	12·7	
14·9	16·1	13·8		12·4	13·4	11·1	
13·5	14·4	12·5		13·4	13·9	12·8	
12·1	12·6	11·6	11·4	13·9	14·2	13·5	12·8
12·9	13·2	12·3		13·7	13·9	13·5	
11·0	11·4	10·9		13·3	14·0	12·7	
10·9	11·5	9·6		11·9	12·8	10·8	
9·9	10·5	9·5		10·9	11·8	8·9	
9·9	10·8	9·2	10·3	9·9	10·2	9·6	9·6
10·7	11·0	10·5		10·4	10·8	10·0	
10·2	10·5	9·8		10·1	10·3	9·9	
10·7	11·1	10·3		9·3	10·4	8·3	
9·8	10·1	9·1		8·5	8·7	8·2	
10·3	10·9	9·9		8·9	9·3	8·5	
9·7	10·0	8·9	8·4	8·0	8·4	7·3	7·8
8·0	8·5	7·0		7·9	8·3	7·0	
7·2	7·8	6·8		7·5	7·8	7·2	
7·0	7·7	6·3		6·7	7·2	6·2	
7·3	7·6	6·7		6·2	6·8	5·5	
6·2	6·6	5·6	6·4	6·3	6·7	5·5	6·5
6·2	6·8	5·8		5·7	6·2	5·3	
6·7	7·1	6·2		6·9	7·5	6·2	
5·6	6·7	4·8		7·0	7·3	6·7	
6·6	6·9	6·0		7·2	7·4	7·0	
6·6	6·9	6·3	7·1	7·6	8·0	7·2	7·7
6·9	7·0	6·6		7·8	8·1	7·4	
7·5	7·9	7·0		7·2	7·9	6·6	
7·8	8·0	7·5		8·6	8·9	8·2	
7·5	8·1	7·0		8·4	8·7	8·0	
7·8	8·5	7·5	8·9	9·0	9·4	8·4	9·7
9·0	9·4	8·3		10·0	10·4	9·7	
9·9	10·8	9·3		10·0	10·3	9·6	
10·3	10·7	10·0		11·1	11·7	10·3	
11·2	11·3	10·6		11·7	12·4	11·0	
12·6	13·1	12·1	11·5	12·3	13·0	11·6	12·4
10·1	12·3	9·1		13·0	13·5	11·6	
11·5	12·1	10·5		12·3	12·8	11·8	
11·8	12·6	10·9		12·6	14·0	11·0	
12·5	13·6	11·5	13·6	13·3	14·4	12·6	14·1
13·6	14·6	12·9		15·0	15·9	14·3	
14·3	15·0	13·5		14·4	14·9	13·6	
14·0	15·5	12·7		13·9	14·4	13·4	
13·6	14·5	12·5	14·2	14·1	14·9	13·2	15·9
12·7	13·9	12·1		15·5	16·9	14·2	
13·1	14·0	12·6		15·9	16·8	15·2	
14·7	15·9	13·6		16·2	16·9	15·7	
15·2	15·5	14·9		16·5	17·6	15·7	
15·3	16·8	13·8		15·4	17·2	14·0	

Table 5.—Timaru Harbour (from 1952-1955 Records). (°C.)

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Mean for month	16·4	17·5	15·9	13·8	11·7	10·1	9·0	—	10·6	11·3	14·0	14·6
Lowest recording	15·3	17·3	15·8	13·0	11·4	9·3	7·6	—	9·7	10·0	13·2	14·4
Highest recording	17·0	17·7	16·0	14·3	12·0	11·0	10·8	—	11·0	12·0	14·7	14·7

Table 6.—Bluff Harbour (from 1952-1955 Records). (°C.)

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Mean for month	16·0	15·1	14·6	12·5	11·3	9·7	8·0	9·0	10·0	12·0	12·6	14·1
Lowest recording	14·6	14·8	14·0	12·5	10·3	9·5	7·6	8·5	9·7	10·0	12·0	13·0
Highest recording	16·8	15·3	15·1	12·5	12·0	9·8	8·6	9·5	10·3	13·0	13·0	15·1

TABLE 7.—Mean Monthly and Extreme Ranges in Temperature (°C)

		Monthly Average			Extreme Readings		
	Year	Highest	Lowest	Range	Highest	Lowest	Range
Auckland	1954	22·6 (Jan.)	11·4 (Aug.)	11·2	23·1 (Feb.)	8·7 (Aug.)	14·4
	1955	23·1 (Feb.)	11·3 (Jul.)	11·8	24·4 (Feb.)	10·6 (Jul.)	13·8
Wellington	1953	17·1 (Feb.)	10·4 (Aug.)	6·7			
	1954	17·7 (Mar.)	9·6 (Aug.)	8·1	18·9 (Feb.)	8·7 (Aug.)	10·2
	1955	17·8 (Jan./Feb.)	8·8 (Jul.)	9·0	20·0 (Jan.)	6·7 (Jul.)	13·3
Lyttelton	1954	19·5 (Feb.)	7·2 (Jul.)	12·3	20·8 (Jan.)	6·1 (Jun./Jul.)	14·7
	1955	19·9 (Jan.)	7·4 (Jul.)	12·5	21·1 (Jan.)	6·7 (Jul.)	14·4
Portobello	1953	16·1 (Jan.)	6·1 (Jul.)	10·0	18·4 (Feb.)	5·2 (Jul.)	13·2
(Otago)	1954	15·9 (Feb.)	6·4 (Jul.)	9·5	17·4 (Jan.)	4·8 (Jul.)	12·6
	1955	15·9 (Dec.)	6·5 (Jul.)	9·4	17·8 (Jan.)	5·3 (Jul.)	12·5
Timaru	1952-55	17·5 (Feb.)	9·0 (Jul.)	8·5	17·7 (Feb.)	7·6 (Jul.)	10·1
Bluff	1952-55	16·0 (Jan.)	8·0 (Jul.)	8·0	16·8 (Jan.)	7·6 (Jul.)	9·2

TABLE 8.—Tidal Variation of Daily Anomalies in Temperature at Portobello (Otago) (1953-54 Summer) °C.

HOURS AFTER HIGH TIDE AT PORTOBELLO (PREDICTED)											
0	1	2	3	4	5	6	7	8	9	10	11
−0·2	−0·6	−0·5	−0·5	−0·1	+0·4	+0·4	+0·5	+0·2	+0·3	+0·1	0

TABLE 9.—Mean, and Greatest Differences between Harbour and Offshore Sea Temperatures for Lyttelton and Otago Harbours. Values in °C by which Harbour Temperatures Exceed (+), or Fall Short of (−) Offshore Temperatures.

		Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Lyttelton*	Mean	+1·5	+1·2	+0·6	−0·3	−0·8	−0·9	−1·7	−0·1	+0·5	+0·9	+1·5	+1·3
	Greatest	(+2·6)	(+2·1)	(+1·4)	(+0·5) (−0·9)	(−1·5)	(−1·3)	(−1·8)	(−0·3)	(+0·8)	(+1·7)	(+2·0)	(+2·2)
Otago†	Mean	+3·1	+3·1	+1·6	−1·5	−2·8	−3·5	−4·1	—	—	—	+1·7	+3·8
	Greatest	(+3·6)	(+3·6)	(+1·6)	(−1·6)	(−2·8)	(−3·5)	(−4·5)	—	—	—	(+2·1)	(+3·8)

*From 1954–1955 records †From 1952–1954 records

APPENDIX

The following is a selected list of publications which report sea temperatures systematically recorded in harbours and coastal localities of New Zealand. Site, type of record and frequency of observations are summarised by each reference. Unpublished records of harbour engineering projects, pollution surveys, etc., are not included.

BATHAM, E. J., 1956: Ecology of Southern New Zealand sheltered rocky shore. *Trans. roy. Soc. N.Z. 84 (2)* : 447-65.

Portobello (Otago Harbour): monthly means from daily readings, 1952-55; seasonal maxima and minima.

BREWIN, BERYL I., 1951: Seasonal changes in micro-plankton in the Otago Harbour during the years 1944 and 1945. *Trans. roy. Soc. N.Z. 79 (3-4)* : 614-27.

Portobello (Otago Harbour): monthly ranges from daily readings, 1944-45.

CASSIE, R. MORRISON, 1956: Spawning of the snapper, *Chrysophrys auratus* Forster in the Hauraki Gulf. *Trans. roy. Soc. N.Z. 84 (2)* : 309-28.

Hauraki Gulf: mean monthly isotherms for November and December, 1950, and 1951, January, 1952.

CRANWELL, L. M.; MOORE, L. B., 1938: Intertidal communities of the Poor Knights Islands, New Zealand. *Trans. roy. Soc. N.Z. 67 (4)* : 375-402.

Mokohinau Is. (N. Auckland, east coast): monthly means for 1929-32 quoted from Hounsell (q.v.), for 1932-37 from ship logs—sporadic surface readings.

DELLOW, VIVIENNE, 1955: Marine algal ecology of the Hauraki Gulf, New Zealand. *Trans. roy. Soc. N.Z. 83 (1)* : 1-91.

Hauraki Gulf and offshore waters east of Coromandal Peninsula: monthly means from ship logs, year(s) not stated.

Inshore waters at Narrow Neck: monthly means from sporadic surface observations, 1949-50.

Auckland and Coromandel Harbours: quotes N.Z. Marine Department records, 1935-38 (q.v.).

HOUNSELL, W. K., 1935: Hydrographic observations in Auckland Harbour. *Trans. roy. Soc. N.Z. 64 (3)* : 257-71.

Auckland Harbour: monthly means for 1929-32 from N.Z. Marine Department records and from observations at Naval Depot (seven times daily), 1931-32.

From same sources, discusses mean annual ranges at Auckland, Tamaki, Russell, and Kaipara; also at Cape Brett, Mokohinau Is. and Cuvier Is. Diurnal range at Auckland Harbour.

KNOX, G. A., 1953: The intertidal ecology of Taylor's Mistak,e Banks Peninsula. *Trans. roy. Soc. N.Z. 81 (2)* : 189-220.

Lyttelton Harbour entrance: monthly means from ship logs, 1929-40.

Annual and diurnal ranges from additional nearshore observations.

MAXWELL, BRIAN E., 1956: Hydrobiological observations for Wellington Harbour. *Trans. roy. Soc. N.Z. 83 (3)* : 493-503.

Wellington Harbour: monthly means from 2 to 3 observations per month, 1953-54.

NEW ZEALAND MARINE DEPARTMENT: Report on Fisheries (Annual reports for the years 1929 to 1941 inclusive).

Monthly means from sporadic surface observations at Auckland, 1928-41; Tamaki, 1918-39; Russell, 1928-41; Kaipara, 1928-41; Coromandel, 1934-41; Whangarei, 1938-41.

OLIVER, W. R. B., 1923: Marine littoral plant and animal communities in New Zealand. *Trans. N.Z. Inst. 54* : 496-545.

Auckland (Queen's Wharf): 2 to 3 surface readings monthly, 1914.

Wellington (Worser Bay): once-weekly readings, 1922.

Portobello (Otago): quotes from Thomson (1905) q.v.

RALPH, PATRICIA M.; HURLEY, D. E., 1952: The settling and growth of wharf-pile fauna in Port Nicholson, Wellington, New Zealand. *Vict. Univ. Coll. Zool. Publ. 19.*

Wellington Harbour: monthly means, monthly maxima and minima, monthly distributions of daily temperatures relative to extremes. From daily surface readings, 1949-50.

THOMSON, GEO. M., 1905: The Portobello Marine Fish-Hatchery and Biological Station. *Trans. N.Z. Inst. 38* : 529-58.

Portobello (Otago): daily surface readings, 1905.

THOMSON, GEO. M.; ANDERTON, THOMAS, 1921: History of the Portobello Marine Fish-Hatchery and Biological Station. *Bd. Sci. Art N.Z. Bull. 2.*

Portobello (Otago): monthly means, ocean and harbour surface daily readings, 1906.